Leaky Wave Antenna: A Historical Development

Vivek Arya, Tanuj Garg

Abstract – **This paper aims to review the work of various researchers for an old and latest advancements on Leaky Wave Antenna (LWA) theory and design. In microwave engineering, the leaky waves had been the most emerging field of research in last few decades. The basis for LWA is a guiding structure that allows the propagation of wave along the length of the antenna structure, with the wave leaking continuously along the structure. This type of antenna is classified into two categories, namely one dimensional and two dimensional LWAs. These LWAs radiate generally at the end fire direction and broadside direction to achieve the maximum scan angle for the radiation beam and these LWAs are uniform, quasi-uniform and periodic. After reviewing the working principles and characteristics of LWAs, an essence of some recent developments of designs have been discussed. Past advances include LWA designs that can scan to the endfire, LWA designs that can scan through the broadside, LWA designs that are conformal to the surfaces, and LWA designs that are capable of power recycling or include active elements. This paper also include the most demanding and latest beam scanning structures, bull's eye structures, full and half mode SIW planar LWA structures and RCS microstrip LWA structures. Some of these novel designs are derived by the recent developments in the field of metamaterials. Some other important development of LWAs such as artificial surfaces, plasmonic leaky wave nano antennas, subdiffractive plasmonic leaky wave antennas and graphene leaky wave antenna also have been reviewed.**

Keywords – **SIW, Leaky wave antenna, Characteristics of leaky wave antenna, Metamaterials.**

I. INTRODUCTION

In the era of globalization, the digital economy is driving an ever-increasing demand for communication bandwidth. For this antenna play very vital and authentic role for communication. The Leaky Wave Antenna (LWA) has been proposed by William W. Hansen in 1940s, then a LWA consisting of a slotted rectangular waveguide was proposed [1]. Leaky wave antennas are the sub-class of travelling wave antennas. They have a guiding structure on which travelling wave propagates and leaks out of a radiating aperture [2]. In last decade, several leaky wave antennas (LWAs) are evolved and analyzed. LWAs have received tremendous attention due to its authentic applications like radar and satellite communication systems because directivity can be enhanced by increasing the number of slots and its beam scanning feature without adding complex feeding systems [3]. Several scholars developed LWAs based on the Substrate Integrated Waveguide (SIW) platform [4-6]. SIW basically maintain the features such as ability to handle high power and Q-factor in planar form [7]. In the designing of SIW, a dielectric material is sandwiched between the two parallel conducting plates which are attached by metallic posts.

The attractive advantages of LWAs are low profile, good beam scanning capability, high directivity and easy fabrication process. For the fabrication of LWAs various material are used like Arlon Cu 2331x, Fr4, Rogger, RT/Duroid 5880 and Gold etc. The speed of development in the field of planar LWAs have increased due to the utilization of metamaterials. This paper include review of recent development of leaky wave antennas. For more information on historical development of leaky wave antennas researchers can referred to [8-12].

Generally on the basis of guiding structure, leaky wave antennas are classified as one dimensional antenna or unidirectional and two dimensional or bidirectional antenna as shown in Fig. 1. In one dimensional (1-D) antenna, the wave is guided in one direction along the guiding structure [11]. The best example of 1-D LWA is microstrip line that is periodically modified to transform the non radiating micro-strip mode into radiating leaky mode. The 1-D leaky wave antenna radiates like a linear array. It either make a fan beam or conical beam at the broadside. The structure is fed at the one extremity, hence wave propagates down the axis of the structure and a centre feed that provides a bidirectional excitation. In two dimensional (2-D) leaky wave antennas, radially propagating leaky waves are used on a 2-D guiding surface for operation [8-10]. They create pencil beam in the broadside direction and conical beam otherwise. In simple words, leaky wave antennas can be unidirectional or bidirectional, depending on whether the source generating the surface wave is at one extremity or at the centre of the antenna. Leaky wave antennas are prominent for microwave band and above bands, because with a simple structure and without complex and expensive feed circuits as used in phased array, they can provide high directivity. LWAs are ideally used for the applications that fetch the advantage of frequency beam scanning. Nowadays, its various applications are fixed frequency beam steering of LWAs, full and half mode SIW planar LWAs [13], composite right/left transmission lines meta-material [14], and Continuous Beam Scanning (CBS) [15].

II. CHARACTERISTICS OF LEAKY WAVES

A leaky wave occur from a closed waveguide structure with some means of periodic or continuous power leakage into the exterior region. A rectangular waveguide with a slotted side wall structure is an authentic example of a leaky wave as shown in Fig. 2. The propagation constant of a leaky wave can be considered as a perturbation of that in the closed

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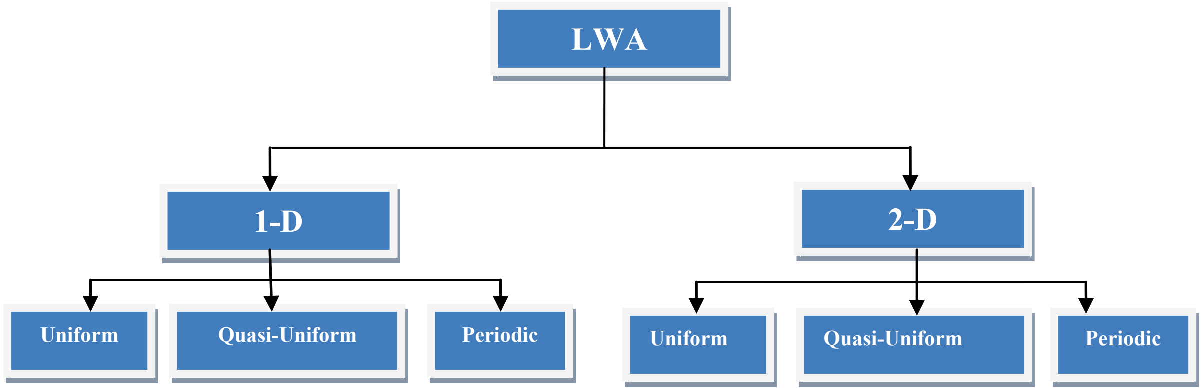

Fig. 1. Classification of leaky wave antenna

waveguide structure. The longitudinal phase constant in the closed waveguide is real (β_c) for lossless guide and perturbed phase constant is complex because it combined attenuation factor. The propagation constant of leaky wave is expressed by $\gamma_z = \alpha_z + j\beta_z$, with both α_z and β_z positive [16]. The attenuation vector α and phase constant β vector are shown in Fig. 2. The attenuation vector α in such a way that the wave is attenuated in the longitudinal direction 'z', although increases exponentially in the transverse direction away from leaky wave structure. As depicted in Fig. 2, leaky wave fields are confined to the wedge defined by the dotted line. The radiation pattern of the leaky wave can be calculated as that of a travelling wave source with γ_z propagation constant and length L of a leaky surface. The radiation pattern with $\alpha_z L >> 1$, is given by [17]:

$$RP(\vartheta) = \frac{\cos\vartheta}{\left|\sin\vartheta - \sin w_L\right|}, \quad (1)$$

where, $w_L = \sin^{-1}\left[(\beta_z - j\alpha_z) / k_0 \right]$ and k_0 is a wave number in free space.

The peak value or maximum value of the radiation pattern occurs in the direction $\vartheta_p \cong \sin^{-1}[\mathrm{Re}(w_L)]$. It indicates the 3dB beamwidth and it is given by

$$BW \approx 2\,\mathrm{Im}(w_L) \approx 2\frac{\alpha_z}{\beta_z}.$$

Now, it is conclude that less the attenuation rate then narrower will be the radiation beam for unidirectional leaky wave. It can be notice that the radiation beam can be scanned in all forward directions except broadside direction ($\vartheta = 0$) because then $\beta = 0$ and the wave in the waveguide is cutoff. To achieve broadside radiation, the leaky wave must be bi-directional in that case two oppositely propagating leaky wave produce a forward and backward directed beams. While the two beam become close to the broadside, they get mixed together in one beam directed in the broadside direction. In this case $\beta_L \sim \alpha_L$ and both are $\ll k_0$ [18]. The radiation pattern for bi-directional leaky wave is given by [17,19]:

$$RP(\vartheta) = \frac{\cos\vartheta}{\left|\sin^2\vartheta - \sin^2 w_L\right|}. \quad (2)$$

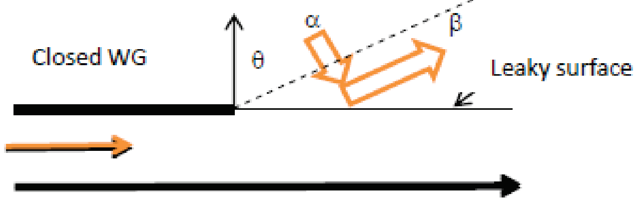

Fig. 2. A rectangular waveguide with slotted side wall acts as a leaky wave antenna

III. Leaky Wave Antennas

The surface waves that are bound to the surface, propagating along the length of the surface and exponentially decaying in amplitude (in perpendicular direction) [22]. At the interface between two materials (free space, metal, dielectric, etc.) the wave is formed.

The surface-wave antennas are the type of travelling wave antennas, where the phase velocity v_p of a wave propagating along the antenna is less than the velocity of plane wave propagating in the free space. Additionally, the strength of the field (along z-axis) in the direction normal to the antenna are exponentially decreased.

The delay-causing structure of antenna is made in the form of metallic perturbing features (ribbed, bumpy, plane or corrugated) to make suitable to be placed onto a dielectric layer. The important advantages of such antenna are that it can be constructed in the form of an insert that projects barely (low profile) from the supporting surface. This most important feature is for installations on aircraft that is restricted by the size of the fuselage and constraints of the shape to improve the flight [110].

The surface-waves antennas are designed according to the Hansen-Woodyard condition to get the end-fire radiation. Modulating the surface along the impedance length of antenna confines the guided wave and a variety of modulations include sinusoidal modulations, tapers and steps etc., which will have to be tested to generate surface wave as a tightly bound [22]. For impedance conditions, the boundary dictates that each of these mode couples to the next lower or higher modes. According to the surface waves nature, the controlling mode and its spatial harmonics which produce slow waves in bound mode. This condition is effective, when protected modulation period is small. In case when it is increased, one or more higher spatial harmonic modes may be unbound in nature from the surfaces and result to a fast wave propagating [23].

A. Classification of LWAs

The classification of a leaky wave antenna is completely dependent on the guiding structure or geometry that propagates a wave in one direction, either *unidirectionally* or *bidirectionally* as shown in Fig. 1. In unidirectional leaky wave antenna, a source is placed at the extremity of the structure. In bidirectional LWA, a source is placed at the centre of the structure. LWAs further can be classified as *uniform*, *quasi-uniform* and *periodic* structures based on the mode of propagation. In uniform leaky wave antenna, guiding structure is uniform along the length (along *z*-direction) of the structure. For uniform LWA, the antenna structure support to fast wave with respect to free space, therefore, complex wave-number of leaky mode $k_z = \beta - j\alpha$, with a phase constant in the range $0 < \beta < k_0$. In other words, uniform leaky wave antennas have invariant transverse cross-section along the longitudinal axis. These antennas utilize a higher order fast wave mode for leaking. Their phase constant is always positive and non-zero $\beta > 0$ for all the frequencies. Due to the phase reversal characteristic, the wave can sometimes be a backward leaky wave.

The working of a quasi-uniform leaky wave antenna is similar in all manners with uniform LWA, except that periodic structure guide to wave. Although, periodicity is very less as compared to wavelength, therefore it don't play direct role in radiation. The guiding structure that supports the wave, which is slow with respect to free space, such that $\beta > k_0$ is called periodic leaky wave antenna. After adding periodicity along the length of the antenna structure the fundamental non-radiating mode radiate. The field on the structure of antenna is characterized by an infinite number of space harmonics (known as Floquet waves) having wave-numbers [24]

$$k_{z,n} = k_{z,0} + \frac{2\pi n}{p}, \tag{3}$$

where $n = -1$ is the spatial harmonic which contribute to radiation and p is the time period along *z*-direction and *n* is the refractive index of the medium. A periodic leaky wave antenna produced beam in either the forward direction or in the backward directions, because $\beta_{-1} = \mathrm{Re}(k_{z,-1})$ can be either positive or negative.

B. Operating Modes of LWAs

There are four type of operational configurations for LWAs, since the antenna structures can be either uniform, quasi-uniform and periodic as they fed either at the one end of the structure (called 1-D LWA or unidirectional LWA) or in the centre of the structure along the length (called 2-D LWA or bi-directional LWA). Different types of beams can be formed which is depending on the configuration. Each operating mode of LWAs is discussed below in detail:

i) ***Uniform/Quasi-Uniform 1-D or Uniform/Quasi-Uniform Unidirectional*****:** The antenna structure is only fed at the one end (z = 0) and an absorber or matched load is connected at other end (z = L) to absorb the residual power. Along the antenna structure the radiating field or current is given by

$$\psi(z) = A \cdot e^{-jk_z z} \tag{4}$$

where A is a periodic function and $k_z = \beta - j\alpha$. In most cases, $\beta > 0$ (forward wave along with positive phase velocity), but for $\beta < 0$ is a backward wave structures. The radiation efficiency due to the load absorption is $e_r = 1 - \exp(-2\alpha L)$. The optimum choice for the efficiency $(e_r) = 0.9$ (i.e., 90%), which enhances the total gain of the given antenna length L [25].

A conical beam is radiated by the structure from the *z*-axis at an angle θ_0, where $\beta = k_0 \cos\theta_0$. The conical beam is in forward direction ($0° < \theta_0 < 90°$) for $\beta > 0$ and in the backward direction ($90° < \theta_0 < 180°$) for $\beta < 0$. The antenna do not radiate exactly at the broadside when the antenna structure supports only a forward wave since $\beta > k_0$. But, if the antenna structure supports either a forward or backward wave, then it radiate at the broadside {as with Composite Right/Left Handed (CRLH) structure}. For this case, a fan beam is received at the broadside. Now, an antenna is capable to radiate at the endfire $(\theta_0 = 0°)$ or backward endfire $(\theta_0 = 180°)$, but this is dependent on the element pattern of radiating source.

The leaky wave antenna (LWA) cannot radiate in endfire and backward endfire direction, when the element pattern of an antenna has a null at the endfire or backward endfire. When the structure radiate at the endfire or backward endfire, then a conical beam will convert into pencil beam as forward or backward endfire is approached. The comparison of different 1-D leaky wave antennas are given in Table I.

TABLE I
COMPARISON OF DIFFERENT EXISTING 1-D LWAS

References	Antenna type	Scanning frequency range [GHz]	Scanning range	Gain [dBi]
120	1-D LWA	10 to 15	-40^0 to $+16^0$	11
123	1-D LWA	32 to 42	-33^0 to 25^0	15
127	SIW-PCB LWA	50 to 70	-45^0 to $+45^0$	15.4
128	Slot array LWA	8.48 to 14.73	-51^0 to $+36^0$	15.05

ii) ***Uniform/Quasi-Uniform 2-D or Uniform/Quasi-Uniform Bidirectional*****:** The antenna is fed at the centre (at z = 0) and an absorber or matched load is connected at the extremities (at the other two ends, $z = \pm L/2$) to absorb the residual power.

For excitation of current or radiating field symmetrically feed is required. Along the antenna structure the radiating field or current is given by

$$\psi(z) = A \cdot e^{-jk_z|z|}\,. \quad (5)$$

A pair of conical beams pointing at $\theta = \pm\theta_0$ is radiated by this structure. The location of the beam maximum for $\beta > \alpha$ for the infinite aperture case $(i.e., L \to \infty)$ is given by [26]

$$\cos^2\theta_0 = (\beta / k_0)^2 - (\alpha / k_0)^2\,. \quad (6)$$

Two conical beams merge together and then create a single fan beam pointing at the broadside $(\theta_0 = 90°)$ when $\beta < \alpha$. For a rectangular or parallel plate waveguide dependent structures, the maximum power radiated by a dipole source at the broadside when $\beta = \alpha$, and narrowest fan beam will be at $\beta = 0.518\alpha$ [26]. By applying same optimum condition an array of 1-D LWAs used to produce a pencil beam at the broadside.

iii) *Periodic 1-D or Periodic Unidirectional*: In this case, the antenna structure is fed at the one end (z = 0) and load is placed at other end (z = L). The slow wave is related to fundamental mode and its start radiating from $n = -1$ space harmonic, which will be forward $(\beta_{-1} > 0)$ or backward $(\beta_{-1} < 0)$.The angle of beam depend on the operating frequency of LWA because it increases as the frequency increases, therefore to scan the beam with frequency such leaky wave antenna is most commonly used. In a single beam operation, to scan the beam from backward endfire to forward endfire, such that only $n = -1$ space harmonics radiates, the effective permittivity of guiding structure (quasi-TEM guiding structure) must be selected so that $\varepsilon_r^{eff} > 9$ [10]. This is equivalent to the condition that $\beta_0 / k_0 > 3$. From Eq. (3), $\beta_0 p = 2\pi$ at the broadside, for periodic structure corresponding to a stopband radiating for a leaky wave antenna is called "open stopband at broadside" [9-10]. Exactly at the broadside many periodic LWAs cannot radiate. At this frequency, the LWA converted into a standing wave antenna and that supports a graphene wave, when all the radiating elements in different unit cells are excited equally. While broadside working of standing wave antenna is possible at one fixed frequency. From the same antenna structure the obtained characteristics will be different when working as a leaky wave antenna at a scan angle different from the broadside. Particularly, there will be a huge difference between input impedance and the beam-width, therefore the characteristics of antenna will change horribly as the antenna scans with frequency through the broadside. It degrade the scan performance near the broadside. A periodic LWA cannot eliminate the stopband problem because it has merely pure shunt or series radiating elements. The newly designed structures are more complex than simple series or shunt elements due to the presence of unit cells. The comparison of different existing periodic leaky wave antennas are given in Table II.

iv) *Periodic 2-D or Periodic Bidirectional*: The periodic leaky wave antenna is fed in the middle of structure to produce a bidirectional leaky wave antenna. When operating frequency of antenna is selected at the stopband such that $\beta_{-1} = 0$, then it becomes a standing wave antenna and radiate only at broadside but no longer behave like a leaky wave antenna. Although, this type of standing antenna could radiate at the broadside such that $\beta_{-1} > 0$ or $\beta_{-1} < 0$. Sometime, leaky wave antenna forged as a transmission line along with a periodic element of shunt or series loads. Hence from this we can conclude that the maximum power radiated at the broadside when $|\beta_{-1}| = \alpha$ [27].

TABLE II
COMPARISON OF DIFFERENT EXISTING PERIODIC LWAS

References	Antenna type	Scanning frequency range [GHz]	Scanning range	Gain [dBi]
120	1-D periodic	10 to 15	-40° to +16°	11
123	1-D periodic LWA	32 to 42	-33° to 25°	15
124	Asymmetric SIW-LWA	12 to 16.5	-32° to +27°	12.5
126	Periodic M-LWA	5.7 to 11.7	145° to 61°	5.9

IV. ADVANCEMENT OF LEAKY WAVE ANTENNAS

In this section, some important and most demanding recent developments in LWAs are discussed. Only the most relevant properties are summarized and representative sample is chosen.

A. End Fire Substrate Integrated Waveguide (SIW) LWA

This create a pencil beam at endfire and its structure is as shown in Fig. 3. It incorporates of Substrate Integrated Waveguide (SIW) along with periodic array of transverse slots [28]. The substrate integrated waveguide works in TE_{10} mode, that's why SIW behave as a rectangular waveguide and made it in integrated form. In SIW, leakage occurs through the transverse slots and the leakage rate is control by their dimensions (leakage is responsible for attenuation constant). The transverse slots are closely spaced, due to which structure become a quasi-uniform leaky wave antenna and starts radiating from the slot-perturbed TE_{10} mode i.e., fast wave. As a result of which the radiated beam is a conical beam, at the endfire $(\theta_0 = 0)$ the beam becomes a pencil beam, when element pattern allows for the endfire radiation.

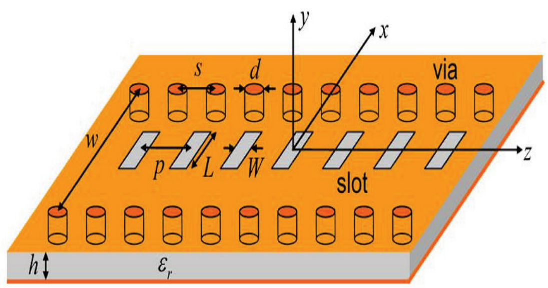

Fig. 3. LWA derived from a periodically slotted substrate integrated waveguide

B. Composite Right/Left Handed (CRLH) LWA

The CRLH-LWA become panacea in the designing of LWA, because without beam degradation [4,29] it was the first structure that successfully scan through the broadside. As discussed in Section 4.2(4), an open stop band at the broadside usually stops the broadside radiation from a unidirectional periodic LWA. Certainly, an open stop band will be generated for the periodic LWA which are having only series or shunt elements. This is a periodic arrangement of capacitor and inductor elements within a unit cell of transmission line and CRLH structure is a metamaterial derived design. The elements which are found in unit cell of transmission line of small length is known as "right handed" elements. Those elements which are artificially introduced is known as "left handed" elements. This is a quasi-uniform structure, because period is small as compared to the wavelength, and this structure of antenna starts radiating from the fundamental $n=0$ space harmonic. For other CRLH-LWA variants, readers can refer [30-39].

C. Quarter-Wave Transformer LWA

After the development of CRLH structure [15], then conventional structure of periodic leaky wave antennas which radiate from the $n=-1$ space harmonic that can scan through the broadside. A novel quarter-wave transformer design was proposed, in which a quarter-wave matching transformer is incorporated into unit cell of a periodic leaky wave antenna [40]. When matching transformer is introduced within the unit cell, obtain the structure as shown in Fig. 4. The quarter-wave matching transformer placed with characteristic impedance Z_T transform the real input impedance R_d to Z_0 by using $Z_T=\sqrt{Z_0 R_d}$. From results, it is observed that shape of beam is preserved as beam scans through broadside like CRLH structure [41].

D. Phase-Reversal LWA

This type of structure is a modification of a periodic leaky wave antenna in which beam scan from backward to forward endfire using lower value of permittivity [42]. {general requirement is $\varepsilon_r^{eff}>9$, as explained in Section III.B(III)}.

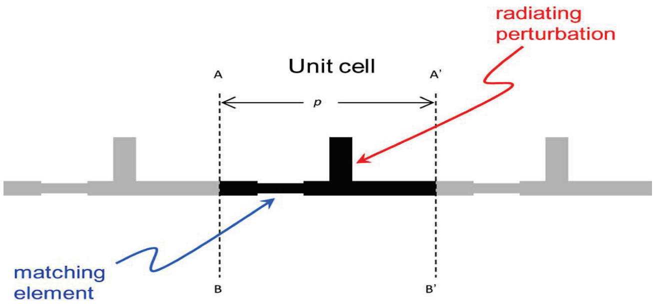

Fig. 4. Structure of quarter-wave transformer leaky wave antenna [40]

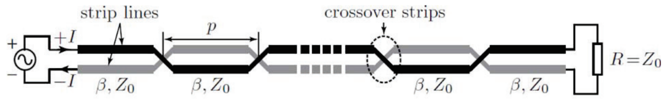

Fig. 5. Geometry of phase-reversal LWA [47]

Phase-reversal LWA design having two parallel microstrip lines printed on the opposite sides of the substrate board, which cross each other periodically as shown in Fig. 5. An "Offset Parallel Strip" (OPS) transmission line is created by microstrip lines. The region where the microstrip lines crosses is the discontinuity by which radiation occurs and although other radiating elements can be introduced within the unit cell [41] of structure.

The crossovers strips in the phase reversal antenna's structure provide a 180^o phase shift in the mode on the OPS transmission line. Recently, few experts introduced 180^o phase shift within the unit cell of periodic structures [24]. The dispersion graphs due to this phase shift is shifted by π {in the Brillouin diagram, a graph of $k_0 p$ versus βp}. As a result of which this shift enables the $n=-1$ space harmonic to reach forward endfire at lower frequency as compared to periodic LWA. As result of which a operation of single beam from backward endfire to forward endfire is feasible only when $\varepsilon_r^{eff}>4$. To eliminate the open stopband problem a creation of radiating crossover that can be modeled as a T network. By using the T circuit as a matching transformer it is only feasible. The beauty of this design is that the beam scans through broadside without degradation [41].

E. Ferrite LWA

A uniform leaky wave antenna produce a beam in the backward direction ($\beta<0$) and needs a peculiar material than simple dielectric and metallic structures. A uniform LWA that has been designed that have this backward wave characteristics is a LWA using a ferrite material. The leaky wave antenna incorporates of a rectangular waveguide that have an open side face due to which radiation takes place [43]. The ferrite material is filled inside the waveguide and an antenna structure works efficiently in a field configuration that is very similar to a TE_{10} mode of waveguide in case when the height is smaller than the width. Multiple modes are found when the ferrite is biased and basically it depends on the frequency band. In single frequency band or in one particular band, the mode is behave like the mode of composite right/left handed leaky wave antenna. When frequency is increases mode transitions will take place from backward wave to forward wave. The ferrite LWA makes possible to the broadside scanning by changing the bias on the ferrite [41,43-49].

F. Bidirectional LWA

As mentioned in Section 3.B(2), a uniform or quasi-uniform leaky wave antenna fed in the middle to make a bidirectional or 2-D LWA and hence produce a beam at the broadside. The leaky wave antenna composed of microstrip and waveguide that's why it become a linear 3-D structure or a 2-D structure in which field is invariant in the one direction. A line source of excitation is used to produce a pencil beam by considering the width of the structure of antenna sufficiently large. Fig. 6 shows that an Electromagnetic Band Gap (EBG) structure and top of a parallel-plate waveguide is filled with a substrate material. The electromagnetic band gap having stack of low and high permittivity dielectric layers with $\varepsilon_2 > \varepsilon_1$ [55]. The height of the parallel-plate waveguide is one-half of a wavelength of dielectric. This electromagnetic band gap design work like a high reflectance surface for the waves inside the parallel-plate region [41]. By using a wire medium [51] an artificial low permittivity grounded substrate layer is developed. A directive broadside beam is produced at an optimum frequency 4.0 GHz. It can be observed that by a homogenized substrate approximation agrees with full wave simulation, which is responsible for the actual wires. For more information on the operation of this type of antenna structure may be found in [52-56].

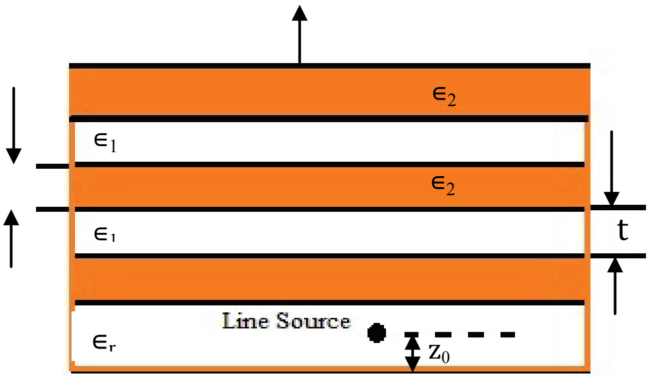

Fig. 6. Electromagnetic band gap structure having alternating low and high permittivity dielectric layers on the substrate

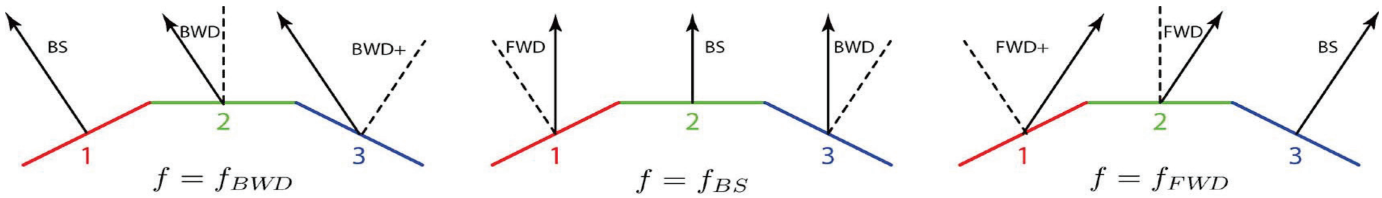

Fig. 7. Sketch of a radiating beam on a three-sided cylindrical surface for a conformal LWA

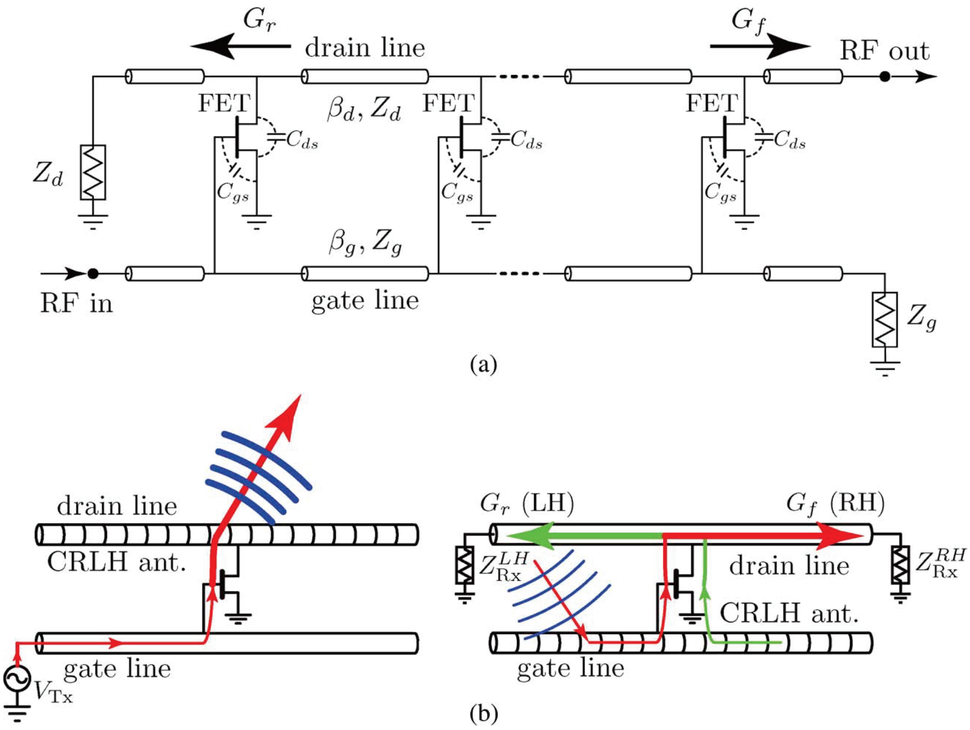

Fig. 8. Active Leaky Wave Antenna: (a) Structure of active distributed amplifier, (b) The CRLH LWA replaced the drain line (left) and the CRLH LWA replaced the gate line (right) [73]

G. Conformal LWA

In this case, a LWA is placed on the curved surface like a cylinder. The shape of cylinder is round and a three sided cylindrical surface is as shown in Fig. 7 [57]. The prime objective of such type of antennas is to provide a narrow beam radiation in a specific predefined direction and it is easily obtained due to the curved shape. It is observed that radiated beam is pointing locally in backward direction for few points and as well as in the forward direction for other points and at broadside for single point on the cylinder as given in Fig. 7. This application needs a LWA that could radiate in both the directions as well as at broadside [58].

A periodic SIW structure based conformal LWA scan its beam from near backfire, backward endfire and through the broadside to the forward direction [59]. Many useful novel conformal leaky wave antenna (CLWA) on a convex surface for Ku Band application has been designed [60-65]. This type of designs ensures the increased efficiency and gain in the Ku-band, along with better return loss curve in terms of its shape and trend [66]. Hence in the development of LWA the conformal structure play very vital role due to enhanced features of leaky wave antenna.

H. Power Recycling LWA

Generally, a leaky wave antenna is terminated with the help of a load at the extremity to minimize the reflections losses. In last few years, various researchers demonstrated the idea for power left over at the extremity of the leaky wave antenna can be recycled back into the leaky wave antenna. As a result of power recycling, the total efficiency of the system [67] increases. A power recycling feedback schemes have been proposed by various experts [68-70] to maximize the poor radiation efficiency of LWAs. The non-radiated power at the end of leaky wave antenna structure, instead of wasting in terminating the load, is fed back at the input of LWA with the help of a power combining system (e.g. Coupler), that constructively adds the input power and feedback powers by ensuring perfect matching and isolation of two signals. Due to which the radiation efficiency of the isolated LWA is increased by the system's gain factor to the total radiation efficiency. It also include dielectric and naturally ohmic losses. Therefore the design of power recycling LWA depends on efficiency, which typically results from a tradeoff between required directivity and restricted size [68,72]. A different type of LWA array with a power-recycling feeding network has designed for the improvement of radiation efficiency. The antenna array is designed by two types of substrate integrated waveguide LWAs with different periodic slots. One type of the LWA is constructed to work on the fundamental ($m = 0$) wave and then radiates in the forward direction. The other one is constructed to work on the -1th ($m = -1$) spatial harmonic and then radiates in the backward direction [71].

TABLE III
COMPARISON BETWEEN OF BEAM SCANNING TECHNIQUES

Type of beam steering technique	Complexity	Losses	Size	Cost	Scanning range
Metamaterials based technique	Medium	High	Medium	High	Low
Liquid crystal-based technique	High	High	Medium	High	Low
Loaded capacitor-based technique	Medium	Medium	Dependent on operating frequency	Low	Medium
Loaded varactor-based technique	Medium	Medium	Dependent on operating frequency	Low	Medium
Loaded stub-based technique	Medium	Low	Dependent on operating frequency	Low	Medium
One gap capacitor-based technique	Low	Low	Dependent on operating frequency	Low	Medium

(a) (b) (c)
Fig. 9. (a) Unit cell of SIW LWA, (b) SIW LWA, (c) HM-SIW LWA [101]

I. Active LWA

Field Effect Transistors (FETs) have been used into an amplifier design that consists two microstrip lines, a "drain line" and a "gate line" connected to drain and gate terminals of the field effect transistors, respectively, as shown in Fig. 8(a) [73]. This configuration used as a (non-radiating) broadband distributed amplifier (DA). For DA-LWA [74], either the gate line or the drain line, or both, can be incorporates along with LWAs, which provide essential and important functionalities. The drain line replaced with an LWA, as shown in left side of Fig. 8(b), using the CRLH structure. This type of structure allow the signal from the source on the gate line to get amplified and then radiated by the leaky wave antenna which is utilized as drain line. The gate line replaced with the leaky wave antenna as shown in right side of Fig. 8(b). An incoming signal that affects on the gate line (LWA) first gets amplified and then sent to the receiver on the drain line. If LWAs, replaced both lines (gate and drain line) then this structure behave as a transponder, which amplifying and reradiating an incoming signal [75].

J. Beam Scanning LWA

This type of antenna is used to enhance the scanning range and gain due to lucrative properties such as low profile, compact structure and wideband performance. The beam scanning LWA, which enables scanning over a wide angle from -35° to +34.5° between 57 and 62 GHz, along with broadside radiation centered at 60 GHz. The LWA design is based on the Composite Right/Left-Handed Transmission-Line (CRLH-TL) concept [76]. LWA based on CRLH was first introduced in [77] and have been observed to provide beam scanning from backfire to endfire [78–80]. Such type of antennas incorporate vias and/or inter-digital structures to develop CRLH-TLs that introduces design and manufacturing complexity of the antenna that has an impact on the cost. Nowadays, there are several beam scanning techniques available.

Comparison of different existing LWA scanning techniques are given in Table III. Which shows that "One gap capacitor-based technique" is superior as compared to other techniques due to low complexity, low losses and cheaper in cost, along with medium scanning range. The standard quality of Chemical Vapour Deposition (CVD) graphene results in a low levels of ohmic losses, as divulged by the first realizations of grapheme dependent devices [81]. The varactor technique, that is loaded on LWAs, has lower cost of production and could be independently controlled [82]. However, network biasing is generally complex and the varactor can only be used at the frequencies below 10 GHz [83], hence limiting its application. The MEMS can switch between the two distinct states, but it have a small and discontinuity tuning range as a tunable mean [84]. MEMS, diodes and ferrites, are mainly used in the leaky wave antenna as a tunable means. Ferrites possess light weight, high permittivity, permeability and high

TABLE IV
COMPARISON OF DIFFERENT EXISTING SIW BASED LWAS

References	Antenna Type	Radiator Length	Scanning Frequency Range (GHz)	Backward to Forward Beam Scanning	Peak Gain (dBi)
94	Periodic SIW LWA (P~ λg)	$\sim 7\lambda_0$	9 to 14	Yes(-35° to +40°)	~12dBi
95	Multilayered CRLH SIW Periodic LWA (P<<< λg)	$\sim 6\lambda_0$	8 to 13	Yes (-66° to +78°)	~9dBi
96	Microstrip CRLH Periodic LWA (P<<< λg)	NA	6.4 to 7.6	Yes (-45° to +37°)	~10dBi
97	Microstrip Based Periodic LWA (P~λg)	$\sim 6\lambda_0$	7.2 to 8.2	Yes (-25° to +15°)	~12dBi
98	Periodic Ridged SIW LWA (P~λg)	NA	8 to 12	Yes (-35° to +35°)	~11dBi
99	Microstrip Based Periodic LWA (P~λg)	$\sim 30\lambda_0$	NA	Yes (NA)	~21dBi
100	Periodic LWA on Goubau line (P~λg)	$\sim 7\lambda_0$	9 to 13	Yes (-13° to 19°)	~11.5dBi
101	Periodic SIW LWA (P~λg)	$\sim 6.84\lambda_0$	10.17 to 16.3	Yes (-38° to +22°)	~11dBi
102	CRLH HMSIW LWA(P<<<λg)	$\sim 5\lambda_0$	8.5 to 12	No (-35° to +37°)	~10dBi
103	Periodic HMSIW LWA(P~λg)	$\sim 8\lambda_0$	10 to 14	Yes (-27° to +23°)	~11.5dBi
104	CRLH HMSIW LWA (P<<<λg)	$\sim 4.85\lambda_0$	13.5 to 17.8	Yes (-66° to +20°)	~16dBi
105	Periodic HMSIW LWA(P~λg)	$\sim 6.84\lambda_0$	10 to 16.5	Yes (-50° to +26°)	~12dBi
121	SSPP LWA (P~λg)	NA	8 to 24	Yes (-45° to +45°)	~12.5dBi
122	SIW LWA (P<<< λg)	NA	10 to 15.7	Yes (-48° to +18°)	~13dBi
123	1-D Periodic LWA (P~λg)	NA	32 to 42	Yes (-33° to +25°)	~15dBi
124	Asymmetric SIW LWA (P<<< λg)	$\sim 2.6\lambda_0$	12 to 16.5	Yes (-32° to +27°)	~12.5dBi
125	SIW LWA(P<<<λg)	$\sim 4\lambda_0$	9.5 to 12.2	Yes (-28° to +30°)	~13.8dBi
126	Periodic M- LWA (P~λg)	NA	5.7 to 11.7	Yes (145° to +61°)	~5.9dBi
127	SIW-PCB LWA (P~λg)	NA	50 to 70	Yes (-45° to +45°)	~15.4dBi

tuning speed [85]. It easily achieve wide scan angle and miniaturization without lowering the value of gain [86]. Although, they involve a high cost of production and strength magnetic field and have large effects on the microwave band devices [87].

K. Bulls Eyes LWA

A Bull's eye antenna is a bidirectional and periodic leaky wave antenna. This takes its name from the visual aspect of the design, which composed of a set of circular corrugations surrounding the central feed [88]. The term "Bull's eye" antenna has also been coined for printed periodic LWAs [89-90]. A corrugated Bull's eye antenna is made from a rectangular sub-wavelength aperture, which kept at the centre of the antenna and then fed from the rear. This aperture launches an electro-magnetic surface wave (called slow wave) travelling at the interface between the conductor material of the antenna and the free space. The dimensions of the sub-wavelength aperture (like: width, depth and length) that control the bandwidth, resonant frequency and return loss of the antenna. The feed is a rectangular-waveguide carrying a linearly polarized TE_{10} mode, due to which antenna is linearly polarized. The E-plane is orthogonal to the surface of the antenna, and coincides with the short side of the sub-wavelength aperture. The H-plane is orthogonal to the surface of the antenna and coincides with the long length of the sub-wavelength aperture [91-93].

L. Full and Half Mode SIW Planar LWA

The SIW and Half Mode Substrate Integrated Waveguide (HM-SIW) periodic leaky wave antennas are developed by various researchers [13,94-103]. Comparison of different existing SIW based LWAs are given in Table IV. which shows that "Full and half mode SIW planar LWA" is superior as compared to other SIW based LWAs due to attractive Continuous Beam Scanning (CBS) feature. The unit cell configuration of SIW LWA followed by the array are shown in Fig. 9 (a and b) and (c) half mode - SIW LWA.

This type of antennas work in both X and Ku bands, that is $\sim 7.5\lambda_0$ in length. It has a maximum value of gain is 12 dBi. The two periodic LWA designs based on SIW and HM-SIW technology are developed [13]. For SIW LWA, the radiation patterns and the frequency responses are very good and the beam angle scans from −38° to +22° with broadside frequency at 14 GHz but for HM-SIW leaky wave antenna, the beam angle scans from −50° to +26° with broadside frequency at 13.6 GHz. Results confirm their strong CBS capabilities through broadside. These LWAs possess advantages like low profile, low cost, easy integration and continuous beam scanning capability.

M. RCS Microstrip LWA

In past, many radar Cross Section (RCS) leaky wave antenna has been designed and analyzed. For reduction of radar cross section of antennas existing methods used metasurfaces, Perfect Absorber Metamaterials (PAMs), Frequency Selective Surfaces (FSSs) and Artificial Magnetic Conductors (AMCs) on all sides of the radiating elements [104-107]. After investigation of Micropstrip LWA (MLWA) for RCS two prominent features are observed: (i) There is a strong function of aspect angle and frequency. As the frequency is increased, the RCS peak changes from the broadside to endfire direction. This process is same as to frequency scanned beam of MLWA. (ii) Second feature is a strong flash that occurs at the broadside along with associated sidelobe patterns in the angular dimension. By modeling the scattering mechanisms separately, the observed features identified as the primary antenna mode scattering, higher-order bounce antenna mode scattering and structural mode scattering [108].

The power reflected in the specular direction is minimum, when the reflection phase difference between consecutive periods is equal to 180°. It has been observed that by changing the surface impedance along with a square wave will provide high gain fan beam similarly as in case of sinusoidal modulation. However, the trade-off for getting a low radar cross section is an enhancement in the sidelobe level because from higher order harmonics radiation occur. Same trade-off exists between the gain or beamwidth and RCS reduction [109].

N. Other Advancement of LWAs

Various other development of LWAs such as artificial surfaces, plasmonic leaky wave nano antennas, subdiffractive plasmonic leaky wave antennas and graphene leaky wave antenna have been done by various researchers [111-119]. Holographic surfaces by addition of impedance artificial surfaces give far field patterns for practical applications [111]. The beauty of such surfaces is that geometrical manipulation of surface impedance is possible, which control the leakage and phase constants [112]. The Sinusoidally Modulated Reactance Surface (SMRS) [113] is used for the designing of artificial surfaces LWAs. In SMRS surface modal impedance surface is sinusoidal modulated. A novel Plasmonic Leaky Wave Nano antennas have been developed which are having low loss properties and confinement of hybrid plasmonic structures along with high directivity [114]. The importance of plasmonic materials increases because of compact resonances occurring at their interface with regular materials (free space or dielectric materials) [115]. A first plasmonic leaky wave naono antenna was based on the planar complementary bilayer in which one layer is of insulating or dielectric material and other is plasmonic [116]. Such type of LWAs are of low profile but they provide high directivity due to sub-diffractive interface resonance complementary materials which can be achieved at optical frequencies along with plasmonic media. Apart from this the directivity can be further increased by varying the some properties of materials having low permittivity [116-117]. In grapheme LWAs, A grapheme sheet is used whose complex conductivity can be modified by providing DC voltages at distinct gating pads throughout design [118-119].

Nowadays, development of LWAs, there is still room for innovation and improvement in terms of the following parameters: (i) wider beam-scanning, (ii) greater directivity, radiation efficiency, and gain (iii) reduction in reflection-coefficient and side-lobe level (SLL), (iv) smaller physical footprint and (v) reduced designing complexity.

V. Conclusion

This paper has discussed the historical development of LWAs. Since 1940s, LWAs are in existence and most of the work is done in the field of planar LWAs due to strong features like low cost, low profile, light weight, easy integration and fabrication. The novel LWAs designs are inspired by recent advances in the field of metamaterials. Several structures which remove the problem of stopband at the broadside and permits for Continuous Beam Scanning (CBS) through broadside have also been reviewed. Some other developments that have been studied and reviewed include LWAs that can scan to endfire and bradside, that can be mounted conformally on the curved surface and that also have power recycling functionality. Active LWAs designs incorporating amplifiers and Bull's eye structures were also reviewed. Some other developments that have been reviewed include beam scanning structures, full and half mode SIW planar LWA structures and RCS microstrip LWA structures.

Various other important advancement of LWAs such as artificial surfaces, plasmonic leaky wave nano antennas, subdiffractive plasmonic leaky wave antennas and graphene leaky wave antenna have been discussed. The knowledge of previous LWAs research, enables the researchers to identify possible paths for future research in the field of LWAs.

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