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# Open Stop Band (OSB) Removal Techniques for SIW-Leaky Wave Antenna: A Review

Akash Mishra, Tanuj Garg, Vivek Arya

*Abstract* – **Major constraint in leaky wave antenna (LWA) is open stop band. In this paper study of different techniques used by researchers to remove the open stop band problem has been done. Different characteristics of leaky wave antenna with the design of substrate integrated waveguide is also discussed. This paper explain theory and design of the unit cell and array of leaky wav antenna in different frequency range i.e. X-band, Ku-band and higher frequency range. Study of various techniques to achieve high beam scanning and higher gain has been done.**

*Keywords* – **Leaky Wave Antenna, SIW, Open Stop Band, CRLH, Asymmetric Technique, RC Technique, Impedance Matching Technique, Ridged Technique.**

## I. Introduction

Traveling wave antennas have received a lot of attention in the last few years [1], and leaky wave antenna (LWA) is the class of travelling wave antenna that leaks the energy or emits the energy [2-6]. Since LWAs have the various features like their low profile, easy to fabricate, high gain and comfortable to integrate with planar configuration [7], they are more preferable by the researcher. First time leaky wave antenna was proposed by W.W Hansen [8] in 1940 and farther the field of leaky wave based on slotted long slot rectangular waveguide was started in 1950-60s by the pioneers Nathan Marcuvitz and A. Oliner [9-10]. Leaky waves have complex propagation numbers ($k_z$). A leaky wave antenna is a fast travelling wave antenna which has a phase velocity larger than the speed of light. It continuously radiate along its length [11].

$$k_z = \beta - j\alpha \tag{1}$$

where $k_z$ is propagation number, α and β is the attenuation constant and phase constant respectively. LWA is classified into two class i.e 1-Dimensional leaky wave antenna (1-D LWA) and 2-Dimensional leaky wave antenna (2-D LWA). It is further categorized as uniform, quasi-uniform and periodic LWA [12-14].

While depending on direction of power radiation, LWAs are classified in two different category, first one is unidirectional i.e. uniform leaky wave antenna which radiate power in forward direction only and second is bidirectional i.e. periodic leaky wave antenna structure which radiates power in both forward as well as backward direction [15-16]. In periodic LWA a beam can be produced in a backward or in a forward direction by increasing frequency at angle $\theta_{-1}$ from broadside is:

$$\sin\theta_{-1} = \frac{\beta_{-1}}{k_0} \tag{2}$$

where θ and $k_0$ is angle measured from Z-axis and free space wave number respectively and $\beta_0$ is fundamental space harmonic.

A leaky wave is produced when a periodic or continuous leakage of power occurs into the broadside of a closed waveguide structure. LWA comprises a transmission line encouraged by the radiating element. Different types of transmission line like micro-strip line [17-19], dielectric waveguide [20-21], rectangular waveguide [22] and SIW are suggested for implementing LWA [23-24]. But these possible transmission line have a problem of open stop band. Among of these transmission lines the substrate integrated waveguide (SIW) is preferred over conventional rectangular waveguides in recent years for their perfect low profile, economical, simple to fabricate and lightweight features [25]. Substrate Integrated Waveguide is a variant of waveguide that bridges the gap between dielectric-field waveguide (DFW) and micro-strip [26]. Various SIW based LWA structures were designed like SIW LWA with H-shaped slots [27], substrate integrated metamaterial based LWA with enhanced broadside radiation bandwidth [28], substrate integrated waveguide leaky wave antenna with transverse slots [29].

SIW leaky wave antenna integrates easily along with other planar circuits and excellent power handling capacity as compared to microstrip LWA. For high power handling capacity and best quality factor, the microwave and millimetre-wave system are designed on rectangular waveguide. But in satellite communication, an antenna with small size is the preferable profile, with high gain, desired radiation pattern and easily integrated with other planar circuits. SIW is a planar waveguide, suitable for millimetre wave application [30]. Some advancements of LWA are mentioned in [31]. Resonant Cavity structure based LWA are also most preferable for significantly enhance gain of a single antenna element [32-37]. The 2-D leaky wave antenna are categorized by leaky-mechanism of the resonant cavity antennas (RCAs) These resonant cavity antennas are composed of partially reflective surface (PRS), which is properly placed above the ground surface plane and between PRS and ground plane multiple reflections perform inside the cavity, which increases the gain of the antenna by in-phase Propagation leaking from structure. There are many works in the literature on the RCAs with frequency scanning capability [38]. With the use of conventional RC structure, a symmetric PRS fed by a main radiator at the center, either conical or broadside beams are achieved. RCA are used for unidirectional beam steering and high gain achievement but

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with the help of SIW LWA researchers achieve high gain and bidirectional beam scanning with use of different materials like Rogger, FR4 etc with different permittivity in HFSS and CST software [39]. In the next section, a detailed explanation of substrate integrated waveguides is discussed so that this paper is useful for researchers who work in substrate integrated waveguide based leaky wave antenna and the problem of open stop band.

## II. Related Substrate Integrated Waveguide (SIW)

For the design of Substrate Integrated Waveguide, the perfect conducting walls are formed with the help of metallic holes/vias inside the dielectric substrate. There are three layers found, the upper and lower layers are normally copper plates and middle layers are formed substrate with different materials like Roger, FR4 etc. The basic structure of SIW is shown in Fig. 1. The performance of SIW is dependent on some key parameters i.e. spacing between the vias denoted by S, vias Diameter (d), distance between via arrays (w) and SIW width (w-effective). The effect of parameter on SIW is to control Radiation Loss and Return Loss by varying diameter and pitch of vias.

$$d<\frac{\lambda_g}{5}, \tag{1}$$

$$S\leq 2d \tag{2}$$

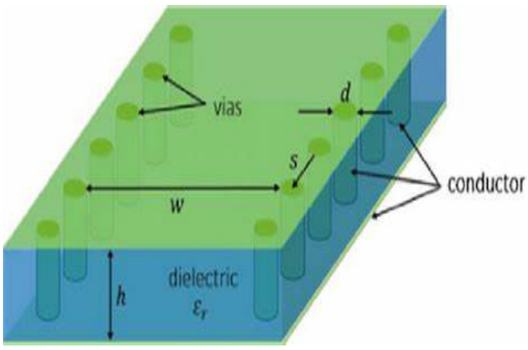



Fig. 1. Top view of 3D Substrate integrated waveguide

$$f_c=\frac{c}{2\pi}\sqrt{(\frac{m\pi}{a})^2+(\frac{n\pi}{b})^2} \tag{3}$$

Where w determined the cut-off frequency and propagation constant of SIW. For rectangular waveguide with dimension a and b, the cut-off frequency ($f_c$) of SIW is given in (4).
For $TE_{10}$ mode, the cut-off frequency is given in (5).

$$f_c=\frac{c}{2a\sqrt{\epsilon_r}} \tag{4}$$

$$w=\frac{a}{\sqrt{\epsilon_r}} \tag{5}$$

where c denote speed of light with value $3*10^8$m/sec, m and n are modes of waveguide and a, b are dimension of the waveguide respectively. Design equation for SIW effective width is given by

$$w_{eff}=w+\frac{d^2}{0.95S} \tag{6}$$

For perfect impedance matching, SIW section consists of a combination of quarter- wave tapered transformer and 50ohm track in series which transform the SIW impedance with standard 50ohm microstrip impedance. The key parameters of tapered line length L and width W connected to SIW are discussed in [40].

In leaky wave antenna two major constraints are there i.e. single beam condition and open stop band (OSB). The centre of attention in leaky wave antennas is the problem of OSB. The most periodic LWA open stop band exists when the beam scanning is performed in broadside. In the OSB region, the attenuation constant changes quickly and drops to zero when $\beta_{-1}$ =0 is reached. Result of changing in attenuation constant, the structure changes from leaky wave to standing wave structure, resulting in this rapid change in bandwidth and input impedance at OSB for longer structure. The problem of OSB has plagued periodic LWA since it was introduced. OSB occurs when two oppositely directed spatial harmonics with same amplitude causes deceleration of the radiation pattern in broadside [41]. The problem of open stop band in leaky wave antenna is shown in Fig. 2. When $S_{11}$ plot is above -10 dBi or $S_{11}$ and $S_{21}$ plot are intersecting each other at any band of frequency range than problem of open stop band introduced.in substrate integrated waveguide, by using vias dimeter and spacing between the vias help to mitigate the OSB. The continuous beam scanning is not possible with the presence of OSB. Perfect impedance matching is key point in leaky wave antenna for removing open stop band. By optimize slot length and width the perfect impedance matching is obtained which reduce OSB.

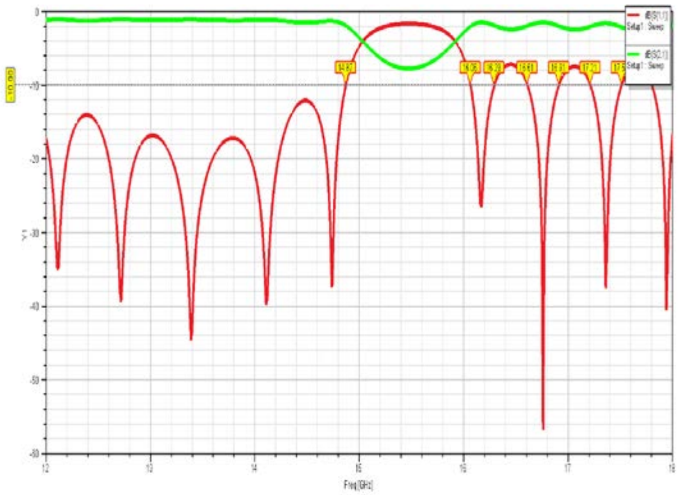


Fig. 2. Open Stop Band Problem in LWA

The problem of open stop band effect in all frequency range i.e. K-band, Ku-band and THz range which affect the continuous beam scanning. For wideband wireless links access, there are considerable interests in terahertz technology. THz technology has magnificent qualities due to its narrow beam, high efficiency, high gain and continuous beam scanning capabilities [71-72]. leaky wave antenna work on THz frequency range have many growing applications i.e. voice-recognizing radar system [73], molecular spectroscopy [74], Terrestrial remote sensing [75] and high transmission rate communication [76-77].

In the next section of paper, we will discuss different OSB removal techniques used by different researchers. There are different types of paper available for removing the problem of open stop bands in leaky wave antennas. But this is only paper where all possible techniques for removing OSB problems in LWA are mention. The detailed expansion of SIW and brief explanation of different techniques available with diagrams of unit cell and array. In the next section the comparison table of all possible techniques are mention. And finally conclusion and acknowledgement are mentioned in the last session.

## III. OSB Removal Techniques

There are various techniques to remove OSB from SIW LWAs. Following are the available techniques:

A. Composite Right/Left Handed LWA
B. Asymmetry Technique
C. Reflection cancellation Technique
D. Impedance Matching Technique
E. Ridged Technique
F. Other Techniques

### *A. Composite Right/Left Handed LWA*

The Composite right/left handed (CRLH) transmission line (TL) is normally used for realizing backfire to end-fire LWA [42-43].A special feature of this type of LWA, which cannot be obtained in conventional LWA, is the backfire-to-endfire ability of LWA (uniform or periodic), which was first signified experimentally in [44-46].

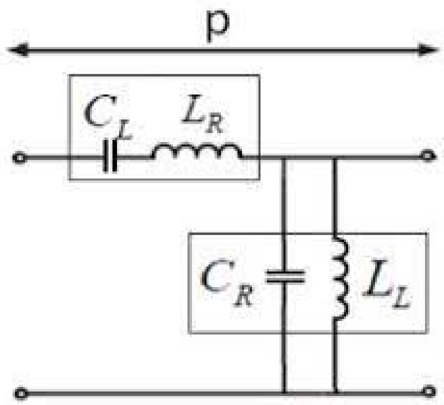



Fig. 3. Typical representation of CRLH equivalent circuit

SIW is a planar platform that demonstrates itself as an excellent possibility for the realization of CRLH LWAs. In open-stop band (OSB) the CRHL technique is most effective and gives qualitative results in broadside and perfect impedance matching at broadside to remove OSB. Representation of equivalent circuit of CRLH is shown in Fig. 3.

Different type of LWA Structure that was proposed with the concept of CRLH-TL are:

#### *(i) CRLH LWA on SIW using S-slot*

S-slot form on the upper plate of substrate integrated waveguide,indicatesthe series capacitance which is mandatory for the realization of CRLH-TL unit cell. These slot on upper surface of SIW i.e patch, prepare the series capacitance ($C_l$) and via's prepare the shunt inductance ($L_l$) [47] as shown in Fig. 4.

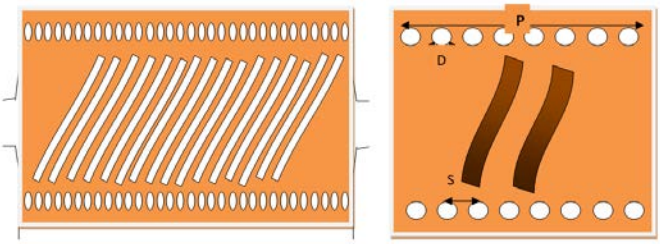



Fig. 4. Unit cell and S-slot CRLH SIW LWA

#### *(ii) Beam-Scanning LWA Based on CRLH Metamaterial For Millimetre-Wave Applications*

The technology used for designing beam-scanning LWA is established on conventional microstrip planer integrated circuits. The proposed antenna structure contains a Square-Slot etched on the upper side of the waveguide. The bottom side of waveguide has the $\pi$-shaped or T-shaped slots [48].

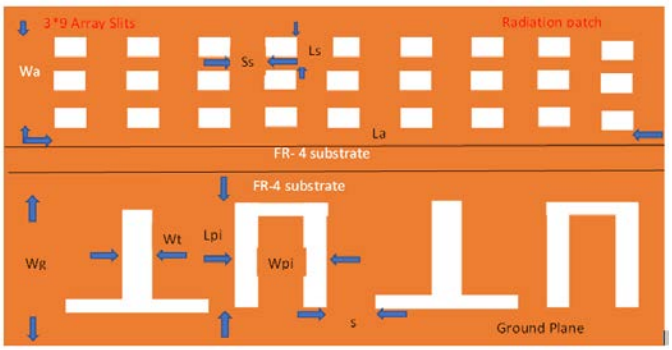



Fig. 5. Top view and Bottom view of Beam scanning LWA

The another structure that is used in CRLH LWA described in [49] uses INTERDIGITAL capacitors for the series capacitance. Latter INSULATOR metal capacitors are used on behalf of interdigital capacitor, which cause negative permeability [50] as shown in Fig. 5. Next structure proposed is the Mushroom structure, which shows forward and backward leakage for desired frequency range which limits their application in the modern day communication process. So introducing electronically scanned LWA incorporating varactor diodes [51-52]. CRLH technique is good for removing OSB but fail to achieve high scanning rate.

### *B. Asymmetric Technique*

The advantage of Asymmetric technique is fully elimination of open stop band problem in broadside and also match bloch impedance at both side i.e at broadside and off broadside, which produce radiation efficiency equalization in broadside.

This technique was issued for open stop band termination and radiation efficiency enhancement for goubau line based leaky wave antennas [53]. The radiation efficiency can be improved with even mode and odd mode analysis and 1-D periodic leaky wave antennas can radiate efficiently for high radiation efficiency. In asymmetry with respect to transversal and longitudinal planes, the even mode can radiate efficiently by leaving the residual polarization as shown in Fig. 6. However in symmetrical with respect to longitudinal and transversal plan, even mode leaves no residual polarisation i.e. it has low radiation efficiency.

A real part of bloch impedance is important for OSB reduction and improvement of radiation efficiency. Asymmetric LWA is designed such that the bloch impedance is real for required range [54] and matching of impedance in both sides i.e broadside and off-broadside bloch-impedance is important for achieving radiation efficiency equalization in periodic LWA [55]. The unit cell (UC) design of asymmetric technique is shown in Fig. 6, in which unit cell has been optimized for achieving the frequency balance condition. The full wave structure is performed for efficiency equalization in broadside by matching bloch impedance at broadside. The impedance method is efficient and peaceful for periodic LWA structure. The asymmetric design has a better result in bloch impedance, dispersion diagram and reflection coefficient as compared to double slot design [56]. This technique is excellent for removing OSB with proper bloch impedance matching at broadside.

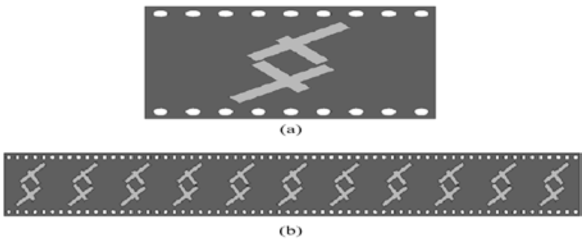



Fig. 5. (a) Unit cell design. (b) Proposed Asymmetrical LWA.

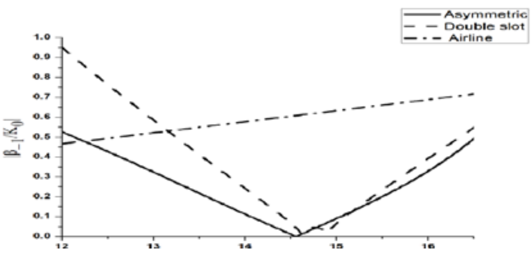



Fig. 6. Dispersion diagram for asymmetric and double slot design [56]

*C. Reflection Cancellation Technique*

In the reflection cancellation technique, at broadside, the first element wave reflection is almost cancelled by the wave reflected by the second element. In the OSB region the attenuation constant extends quickly, so bandwidth and scan angle leads to rapid variation. Separate this variation by using two strip unit cell and amplify the feature of dielectric-inset double strip structure.

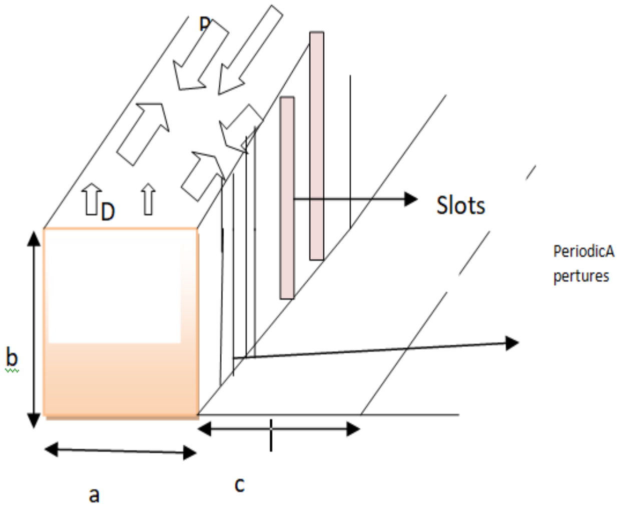



Fig. 7. Dielectric Inset LWA Using Double Strip Grating

To reduce significantly open stop band problems, the antenna is designed with two radiating elements which indicate how a metallic strip unit cell can completely eliminate the OSB as shown in Fig. 7. The basic concept of OSB elimination was presented in [57-58]. Implementation of suitable transverse equivalent network (TEN) circuit for dissimilar space harmonics, the transverse equivalent network is radiating transition in free space to air-filled waveguide. The short-circuit length of dielectric parallel plate waveguide by scraping suspension at air-dielectric interface.

The cause for introducing strips within the unit cell is to decreased the effect of OSB in broadside by developing transverse equivalent network based LWA which modified dielectric inset waveguide loaded with the aid of periodic two strips array and two apertures per unit cell [59] . In order to remove OSB, cascading of unit cells is also used for fully suppression of OSB. Combination of matched unit cells along the propagation direction is useful for continuous scanning and characteristic impedance matching at the broadside [60]. This technique removes the Open Stop Band problem but for achieving high gain and scanning rate Asymmetric Technique and Impedance technique is best.

*D. Impedance Matching Technique*

Most of the technique can remove the problem of OSB but not achieve best impedance bandwidth in broadside for limited beam scanning range. A SIW based unit cell accommodates a longitudinal slot and inductive post, whose positions are opposite from the centre of unit cell. To achieve perfect impedance matching a combination of longitudinal slot and inductive post give inductive and capacitive effect. In the top metallic plate the longitudinal slots position are away from the midline for surface current radiation. The direction of the main lobe changes with frequency at broadside direction.

The direction of main beam for $n^{th}$ space harmonic is given by:

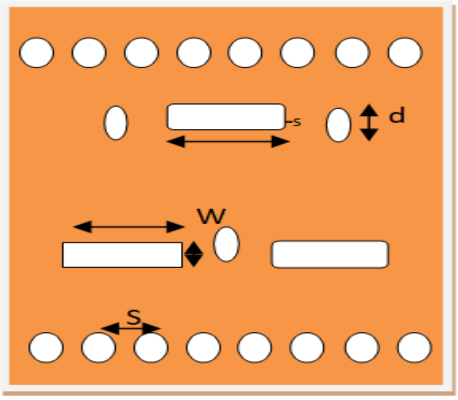
$$\theta_n = \sin^{-1}\left(\frac{\beta_n}{k_0}\right) \tag{7}$$

where $\beta_n$ is phase constant for $n^{th}$ space harmonics i.e,

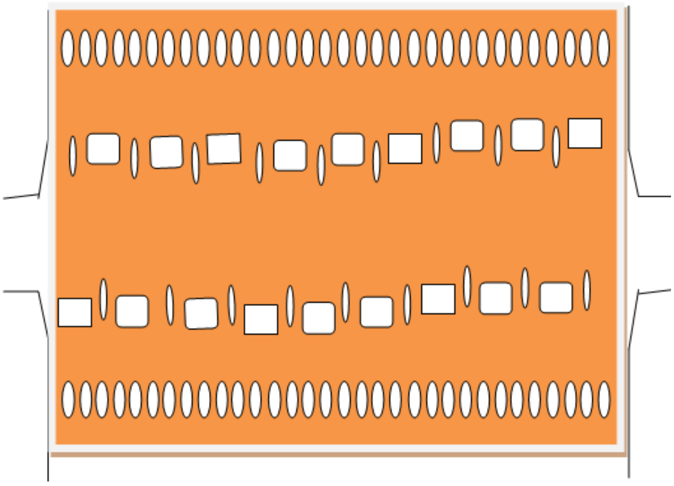
$$\beta_n = \beta_0 + \frac{2\pi n}{P} \qquad (8)$$

and $k_0$ is free space wave number.

Radiation angle $\theta_n$is either zero, negative or positive which indicating backward, forward and broadside radiation. For radiation of fast wave antennas $|\beta_n| < k_0$.




(a)



(b)

Fig. 8. Configuration of SIW periodic LWA structure: (a) 3D and (b) top view

The SIW based structure is coded with conductor on both side top and bottom of the substrate to form waveguide, in conjunction with metallic via rows at edges which show in Fig. 8. The impedance matching technique with different slot positions is explained in [61-65]. With use of longitudinal slot and inductive post this technique is most popular technique for removing OSB in leaky wave antenna.

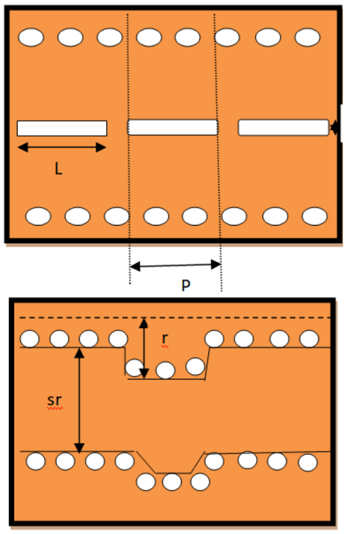
*E. Ridged Technique*

A periodic collinear-slotted LWA with double ridged SIW structure as shown in Fig. 9, which is a slow wave and discontinue slots are placed in centerline without displacement. Characteristics of Ridged Substrate Integrated waveguide (RSIW) structure is changing because radiation can take place in center line and cross-polarization in structure is reduced because the slots do not have an offset from center-line. The basic structure of the PLWA is a sit up of SIW whose dominant mode is slow wave. A space harmonic can be activated directly by creating discontinuities or periodic modulation in structure, for this motion array slots are formed on the upper plane of Substrate Integrated Waveguide. With use of proper sidelobe level (SLL), the field distribution in the slot has been controlled for radiation pattern and just because of this inside the E-field, the slot is managed by varying offset from the center-line. So for the required pattern, the structure of substrate integrated waveguide remains undamaged and the discontinuities are changed and cannot be categorized as a periodic LWA structure. Two ridges are placed inside the structure and slots position remain fixed and distribution inside slots can be managed by varying the dimension of ridges structure. The incoherence element which is Ridged SIW and fixed slots is changed and dispersion relation is depending on dimension of the structure. Radiating slots have an offset from the middle line of symmetric SIW shape. To create a second- order bean and increase in cross-polarization of structure which processes a corresponding substandard cross-polarization of above -25db. But if slots are placed in the middle line and generate symmetry array elements, the cross-polarization is reduced.

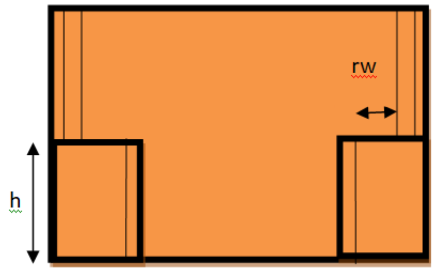
In Fig. 9 the two substrate with height h and dielectric constant $\epsilon_r$ are shown in Fig. 9. Slots length $l_s$ and period P are located on the middle line of top substrate, distance between the vias in top substrate is a. And for realizing the ridges, the lower substrate is used, located on both sides of the slots [66-67]. With use of double ridged SIW structure OSB remove and vias help to achieve perfect impedance matching. This technique removes OSB and gives high gain with high scanning rate.

*F. Other Techniques*

Some other novel techniques are used for suppression of OSB in leaky wave antennas. i.e. a novel SIW LWA for non-stop beam scanning from backward to forward. The SIW based Leaky Wave Antenna has excellent power handling capacity, low profiles, lightweight and easily integrates with other circuits.




(a)




(b)

Fig. 9. Collinear slot array RSIW leaky wave antenna

In one of the techniques to remove open stop band problem a novel unit cell based impedance matching technique is used, where unit cells consist of rectangular-shaped H-plane and longitudinal slots. That has a waveguide junction and exhibits inductive effect [68-69]. It compensates for the effect of the capacitor in the longitudinal slot and comes up with perfect impedance matching. The unit cell is designed with two metallic via rows placed in direction of propagation which play the same role of perfect conducting waveguide wall as shown in Fig. 10.

The unit cells are designed with two longitudinal slots placed opposite the pinnacle plate of the array antenna, which increase the wide variety of slots as radiating elements enhance radiation overall performance and maximum gain. Some other arrays wherein the radiation detail are placed on pinnacle aspect wall, so due to coupling effect the cross-polarization level is excessive and antenna array configuration can modify this issue and decline cross-polarization level.

Main beam direction is change with frequency for periodic LWA, the main beam direction is related with phase constant for $n^{th}$ harmonic is

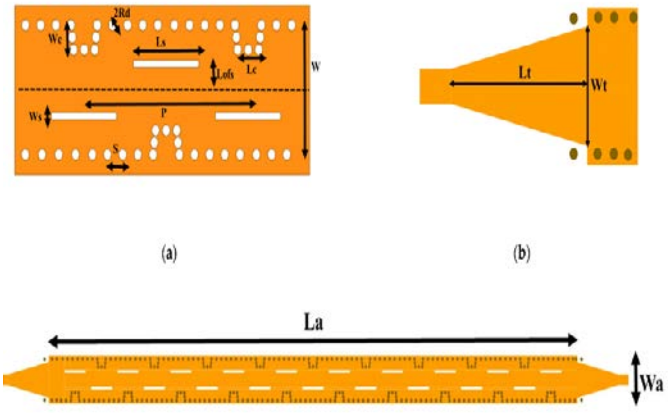
$$Q^{n}_{main-beam} = \sin^{-1}\frac{\beta_n}{k_0} \tag{10}$$

$$\beta_{n=\beta_0+\frac{2\pi n}{P}} \tag{11}$$

where $\beta_0$ is propagation constant of dominant $TE_{10}$ mode and $k_0$ is free space wave-number, P denote period of array.

Due to the main beam route converting with frequency can offer the frequency beam scanning capability for -1$^{st}$ space harmonic. In Fig. 10, formation of unit with longitudinal slot and rectangular-shaped H-plane where longitudinal slots are placed offset from middle and on metallic plate in SIW. The longitudinal slot length and distance from the middle-line slot are selected such that it provides capacitive effect. So capacitive effect are compensated by using metallic vias in longitudinal slot, it may offer perfect impedance matching for Open Stop Band suppression [70].

All technique are used for removing the OSB problem but Asymmetric technique, Impedance matching technique and Ridged technique is most effective for achieving high gain and scanning rate.




(c)

Fig. 10. Proposed SIW LWA(a) unit cell, (b) microstrip to SIW transition proposed design and (c) array configuration [70]

TABLE 1
COMPARISON OF DIFFERENT TECHNIQUES

| Ref. | Technique | Complexity | Cost | Performance |
|---|---|---|---|---|
| [47] | CRLH using S- slot | Less | Cheap | Excellent |
| [56] | Asymmetric technique | Moderate | Cheap | Best |
| [59] | RC Technique | Less | Cheap | Good |
| [61] | Impedance matching technique | Moderate | Cheap | Excellent |
| [67] | Ridged Technique | High | Expensiv e | Excellent |

## IV. CONCLUSION

This paper has discussed the introduction and classification of Leaky Wave Antenna. Design of Substrate Integrated Waveguide with features of low profile, low cost, lightweight and planner circuit. Different SIW based Technique used by researchers for suppression of Open Stop Band problem introduced in LWA. Composite Right/Left Handed LWA technique with S- slot is used for beam scanning -33 to +25 degree. The frequency ranged from 32 GHz to 42GHz with high gain value 15 dBi. Asymmetric technique is used for suppression of OSB with beam scanning -32deg. To +27 deg. and constant gain 12.5 dBi. Double strip grating Reflection technique used for beam scanning in broadside and removing OSB. Impedance matching techniques perform maximum gain of 14.2 dBi and beam scanning from -49 deg. to +69 deg. through the broadside. Collinear slotted rigid technique measures cross-polarization and SLL has a value of -25 to -45 dB. Dielectric Image line work on Ku-band and suppression of OSB with beam scanning -65 deg. to 30 deg. With the help of knowledge of different researchers we identify the possible method or technique for removal of OSB in Leaky Wave Antenna. In the future, it will help new researchers to find some novel techniques for suppression of Open Stop Band in LWA.

ACKNOWLEDGEMENT

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