A Comparative Study of Microwave Rectangular Waveguide-to-Microstrip Line Transition for Millimeterwave, Wireless Communications and Radar Applications

Atul Varshney, Vipul Sharma

Abstract — **The day-to-day technological development of wireless communication, RADAR and millimeter wave applications has increased the need of planar circuits like MMIC, MIC to connect with waveguide section horn antennas with transmitter/receivers section and the time demands a low loss transition interconnect between microstrip line and waveguide. In this paper a detailed study of a microwave rectangular waveguide-to-microstrip line transition has been presented in tabulated format for easy understanding of transitions along with their merits, demerits and coupling methodology used to design transitions and the results in terms of insertion loss (IL), return loss (RL) and fractional obtained bandwidth have also been presented. The specific applications of the designed transitions for RADAR, millimeter wave and wireless communications, etc. are displayed in the table. The methodology (procedure) steps to design transitions have been also listed for future improvement in transition design.**

Keywords — **Microstrip line, Rectangular waveguide, Microwave transition, Millimeterwave, HFSS.**

I. Introduction

The most promising challenges of the present time are to develop a transition with lower return loss (RL) and highest transmission, i.e. higher insertion losses (IL) along with wide fractional bandwidth and to develop such a microstrip to waveguide transition and vice-versa for millimetre wave applications. That is why the changes are made to be done in the existing transition technology. These transitions are also known as hybrid transitions (adaptors). All these required values of parameter, i.e. RL, IL and bandwidth can be achieved by proper field and impedance matching between the two dissimilar geometries of transmission lines needed for transitions. Field matching represents a prerequisite to a transition. Impedance matching, instead, provides maximum coupling between the two transmission lines while minimizing reflections. The better field matching and impedance matching are also required for the maximum power transfer between the two transmission lines. Previously, the scientists and researchers have achieved impedance matching by the use of impedance transformer, via holes (fences), irises and the windowing methodology etc. In my work, our prime focus is same to achieve impedance and field matching with improved performance of desired parameters by the use of different methodologies. Rectangular waveguides were one of the most primitive types of transmission lines used to transport microwave energy and still used today for many applications.As we know that the microstrip lines are planar transmission lines and most suitable to collect power (and transfer power) from (and to) planar MIC and MMIC circuits and antennas at microwave and millimeter wave applications easily.Because of the recent trends toward miniaturization and integration, a lot of microwave circuitry is currently made-up using planar transmission lines, such as microstrip or strip line, rather than waveguide. There is, however, still a need for waveguides in many applications such as millimeter wave systems, and in some precision test applications.

Article history: Received November 04, 2020; Accepted December 23, 2020

Atul Varshneyis with Electronics and Communication Department, FET, Gurukula Kangri University Haridwar, Uttarakhand, India, E-mail: atul26_sit@rediffmail.com

Vipul Sharma is with Electronics and Communication Department, FET, Gurukula Kangri University Haridwar, Uttarakhand, India, E-mail: vipul.s@rediffmail.com

II. Literature Review

There is different type of transitions available in the field of microwave to couple electromagnetic energy between the same type of transmission lines and dissimilar type of transmission lines. When same type of dissimilar aperture dimensions (say waveguides with different cross-section areas) transmission lines couples their energy to each other these are called as Auto transitions. However, when two dissimilar transmission lines say one waveguide and other coaxial cable or waveguide and microstrip line etc. couples their energy are called hybrid or cross transitions [25]. Such structures are also known as adaptors or electromagnetic energy launchers. Waveguide to coaxial cable transitions are used up to 10GHz frequencies. Nevertheless, for frequencies higher than the 10GHz these transitions having their limitations and a new transition is required to work well at microwaveand millimeter wave frequencies. Microstrip line for rectangular waveguide transition becomes very popular to use at microwave frequencies and millimeter wave frequencies. As the most of the RF modules, receiver and transmitting antennas, filters etc. are fabricated on MIC, MMIC or HMIC and horn antenna are first choice to collect Electromagnetic energy and couple this energy into the rectangular or circular waveguides.

There are mostly two types of microstrip line to rectangular waveguide transitions namely first inline or 0° and right-angled or 90° transition depends upon the microstrip line energy interaction with rectangular waveguide.

In inline transition,microstrip line is inserted along the length of the waveguide to couple the electromagnetic energy into the rectangular waveguide. Insertion of microstrip is also two types; it depends upon the style of insertion of insertion of microstrip line along parallel to magnetic field or along parallel to the electric field (transverse to the magnetic field) of the rectangular waveguide. Thus, these inline insertions are also known as 0° transition [1, 2, 4, 10-11, 28, 30-31] or 90° inline transitions [5, 10, 13, 20 and 23]. The main features of these transitions are simple, occupies less space, planar structures, easier to fabricate and integration, as a result these provide mass productions.

Similarly, right-angled microstrip transitions are based on the principle of insertion of microstrip line transverse to the direction electromagnetic energy flow into the waveguide. In other words, we can say that the insertion of microstrip energy is coupled to rectangular waveguide at 90° to the main energy flow direction. The 90° insertion of microstrip line in waveguide either along the width of the waveguide or height of the waveguide. Thus, these transitions are also known as broadside wall and narrow side wall transitions. These occupy more space and huge volume in comparison to inline transitions. Nevertheless, these transitions have a better return loss and broaden bandwidth. The only disadvantage of these structures is its complexity. [3, 6-9, 12, 14-17, 21-22, 24-27, and 29].

Since, the impedance of microstrip line has been 50 Ω that is very less in comparison to the impedance of rectangular waveguide impedance (approximately 500 Ω). So that proper impedance matching is essential between the two transmission lines of this hybrid structure to couple maximum energy. This could be achieved with the help of steps quarter wave transformer [3], tapered microstrip line and multi-section Chebyshev transformer [11, 28, 30, and 31] and tapered transformer [30]. Multi stepped quarter wave transformer and Notch Cut on the Strip [20] are the top choices of the authors for this purpose.

Since, field distribution mode on microstrip line is quasi-TEM mode and that of in rectangular waveguide is either transverse electric (TE) or transverse magnetic (TM) modes. Therefore, the field matching becomes a necessary part to design any such kind of transitions. For this purpose, dielectric field rectangular waveguide (DFRW) [11], Radial shaped probe for field matching [20] and a section of ridged waveguide with stepped ridges [2, 13, and 31]. Nevertheless, the field matching is simply achieved by making changes in the shape and size of the waveguide.

There are many technologies/methodologies are used to interface EM energy transmission between these lines. Probe insertion [6, 15], aperture coupling [6, 8, 12, and 17] and slot coupling [7, 22] or their combination is the most popular one for this purpose. These couplings provide better return loss and low insertion loss and narrow bandwidth. So that such transitions those using these methodologies are having very limited applications in the millimeter and microwave frequencies. Therefore, bandwidth enhancement is the prime focus of the current research. In some cases, authors utilizes a semi-circular microstrip ring [3], tapered line with circular head at top, quasi Yagi-Uda antenna, semi-circular loop works as a loop antenna [23], differential microstrip patch antenna (DMPA) [24], Broadside Coupled Micrstrip Line (BCML), bow-tie antenna [26], Transitions using the radial probe and extended GND planes [27], a dipole antenna, truncated ground and a CPS balun [5, 13], U-shaped slot structures [4], Via-holes [10, 19, 24 and 27], groves [10], window, iris [9], via fences [22], Coplanar strip (CPS) probe [18], extended ground and extended microstrip probe [6, 12, 22, 27 and 29], uses multiple probes etc. Thebandwidth enhancement could be achieved with the help of metamaterial like structures such as complementary split ring resonators (CSRRs) [2], triple patch probe [29], tapered microstrip lines [30], microstrip antenna [16, 17] are the recent technologies. A precise review is tabulated in Table I.

III. Design Methodology

The following steps have been followed to design any rectangular waveguide-to-microstrip transition:

I. First, choose microwave band of design interest.
II. Decide the design frequency.
III. Select the standard rectangular waveguide for the design operating frequency
IV. Calculate the waveguide parameters like cut-off frequency, guided wavelength and impedance for waveguide TE_{10} mode.
V. Now calculate back short distance $\lambda g/4$.
VI. Calculate the width of 50-ohm microstrip line for operating frequency and chosen suitable substrate for this frequency.
VII. Calculate the length of quarter wave transformer ($\lambda g/4$) to match the impedance of line to inserted conductor microstrip inside the waveguide.
VIII. Cut the aperture of the rectangular waveguide either along the line or at right angle to the propagation of RF energy.
IX. Note that the width of aperture and substrate are same and height of cutting aperture is lies between 2 times to 2.5 times of the substrate height.
X. Insert the upper conductor of microstrip and remove the ground from the inserted substrate.
XI. Now optimize all variable parameters like back short distance,width and length of quarter wave transformer and probe untilto get the betterinsertion loss and lower than 10 dB RL fractional bandwidth.
XII. Note that the length of the waveguide and microstrip lines are chosen integer multiple of half wavelength of guided wavelength.

A. Transition Design

Fig. 1 shows the in-line 0° microstrip line to standard rectangular waveguide WR-10 transition using microstrip line Chebyshev transformer and microstrip linear taper [30]. Both methods match the low impedance with high impedance and field of TE10 mode of rectangular waveguide with quasi-TEM mode of microstrip line.

Fig. 2 shows the 90° microstrip line-to-rectangular waveguide (WR-12) transition with liquid crystal polymer (LCP) dielectric material and extended ground it achieves 71.7% broad bandwidth [29].

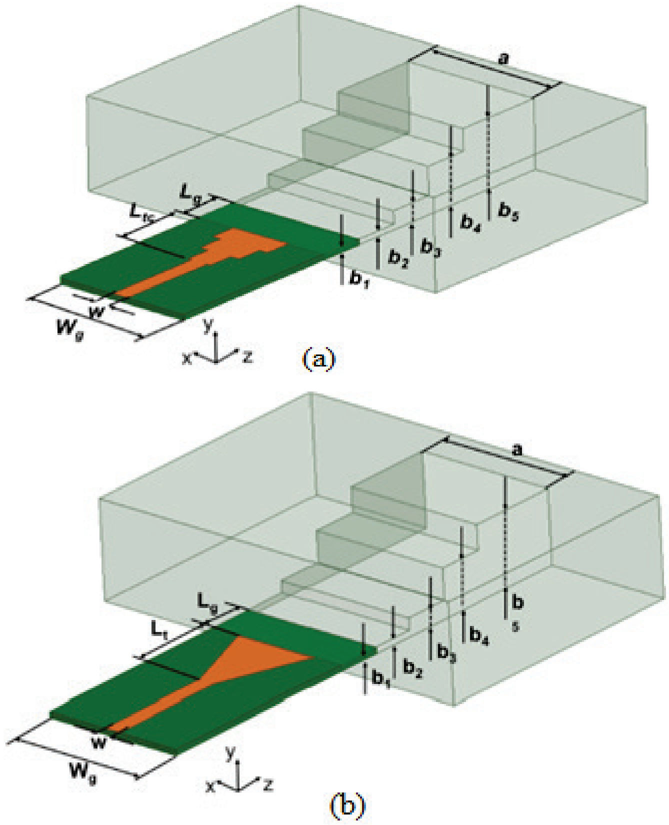


Fig. 1. Microstrip to rectangular waveguide (WR-10) transition
(a) In-line (0°) Chebyshevmicrostrip transformer
(b) In-line (0°)microstrip linear taper transformer

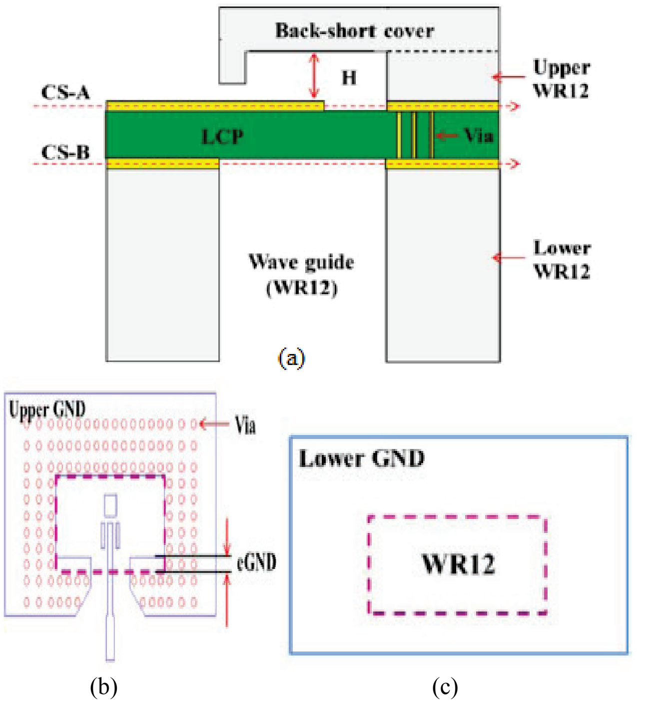


Fig. 2. 90° Microstrip line to rectangular waveguide (WR-12) transition

Fig. 3 shows the quarter wavelength broadside coupled microstrip line to rectangular waveguide transition that utilizes the bow-tie element at the launchers end [26].

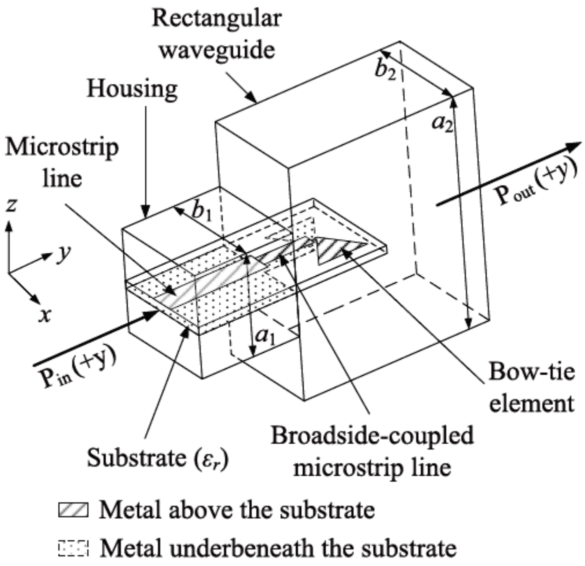
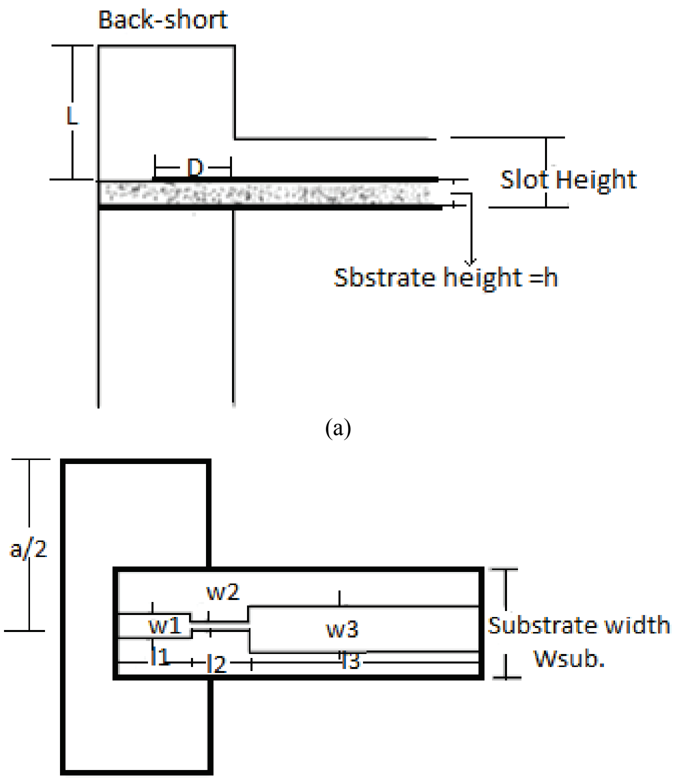
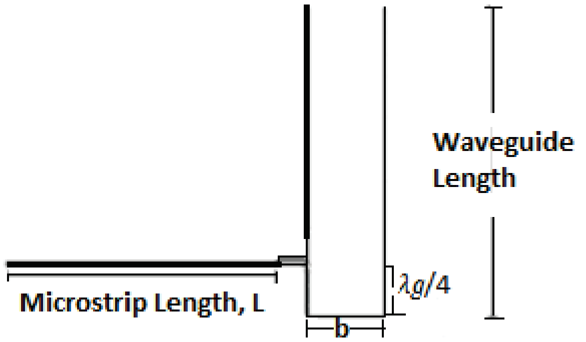


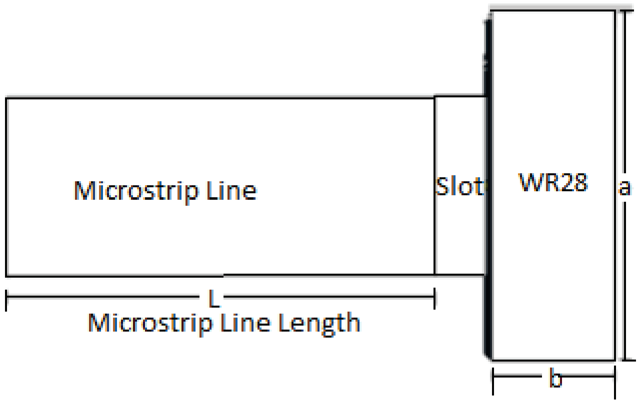
Fig. 3. 90° Microstrip to broadside coupled waveguide transition

Fig. 4 shows the simplified microstrip line to waveguide (WR-28) transition that utilizes the quater wave transformer for impedance matching as shown in Fig. 4(e). Figs. 4(a-d) represent slot coupling and insertion of microstrip line with top and side views into the rectangular broad wall at 90° insertion [25].

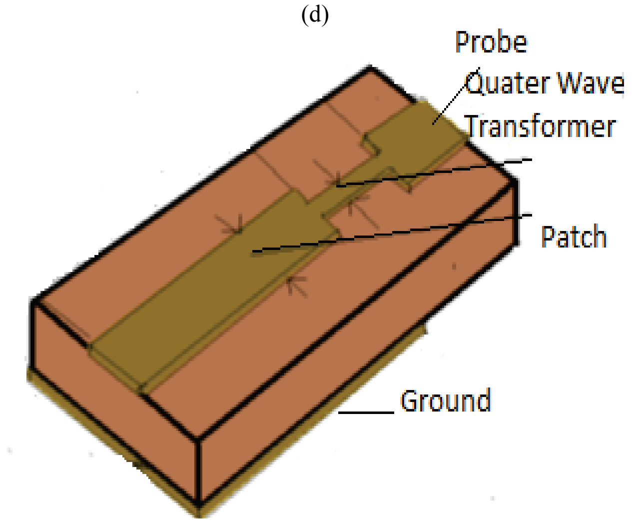




(c)



(d)



(e)

Fig. 4. Simple microstrip line to rectangular waveguide WR-28 transition: (a-d) different views of transition and (e) inserted microstrip line view

B. *Transition Design Equations*

(i) MICROSTRIP LINE CALCULATIONS [36]

1. The effective dielectric constant

$$\varepsilon e = \frac{\varepsilon r + 1}{2} + \frac{\varepsilon r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-1/2}$$

where:

εe = Effective dielectric constant or permitivity of microstrip line

εr = dielectric constant of substrate

w = width of microstrip

h = height of substrate chosen

2. Characteristics impedance

$$Z0 = \frac{60}{\sqrt{\varepsilon e}} \ln\left(8\frac{h}{w} + \frac{w}{4h}\right) \quad \ldots \ldots \text{for } \frac{w}{h} \le 1$$

$$Z0 = \frac{120\pi}{\left(\sqrt{\varepsilon e}\right)\left[\frac{w}{h} + 1.393 + 0.667 \ln\left(\frac{w}{h} + 1.444\right)\right]} \quad \ldots \ldots \text{ for } \frac{w}{h} \ge 1$$

3. Microstrip width

$$w = \frac{c}{f0}\sqrt{\frac{2}{\varepsilon r + 1}}$$

where f_0 = designed frequency.

4. Width of substrate and ground
$W_{sub.} = W_{gnd.}$ = 9 to 10 times width of microstrip i.e. ,

$$W_{sub.} = W_{gnd.} = 9w \text{ or } 10w$$

(ii) RECTANGULAR WAVEGUIDE CALCULATIONS [37]

1. Wavelength

$$\lambda = \frac{c}{f0}$$

c = light velocity

2. Dominant modes

TE_{10} and TM_{11}

3. Cut-off frequency

$$fc = \frac{c}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

where m = 1 and n =0 for TE_{10} mode, a = breadth of waveguide and b = width of waveguide.

4. Guided wavelength

$$\lambda g = \frac{\lambda}{\sqrt{1 - \left(\frac{fc}{f0}\right)^2}}$$

5. Waveguide impedance

$$Zg = \frac{\eta}{\sqrt{1-\left(\frac{fc}{f0}\right)^2}} \quad \ldots \ldots \textit{for TE mode}$$

$$Zg = \eta\left(\sqrt{1 - \left(\frac{fc}{f0}\right)^2}\right) \quad \ldots \ldots \text{for TM mode}$$

where

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

6. Waveguide Back-short distance

$$D = \frac{\lambda g}{4}$$

7. Waveguide length

$$L = N\frac{\lambda g}{2}$$

where N = any integer value other than 0.

C. *Transitions Review Table*

A comparative precise, compact author wise collection of methodology/technology used in different transitions, their merits and demerits, applications along with the obtained results have been tabulated inTable I.

TABLE I
COMPARATIVE STUDY OF TRANSITIONS

Ref.	Tran. type	Refrred WG	MW freq. band (f_1-f_2 GHz)	RL (dB)	IL (dB)	BW (%)	Coupling Methodology used	Merits & Demerits	Applications
[1] E. Hassan et al. 2019	In-line (0°)	WR-42	K-band (20-28)	>15	<0.35	10	. Signal coupling between a MSL and a RWG by optimizing thedistribution of copper in two design domains	. compact . most cost effective . excellent shielding . low attenuation . low bandwidth	. Using standard PCB technology, the transition can be directly used to integrate into the sensor at the lowest possible cost.
[2] Y.Ren et al. 2019	End inserted (in line)	WR-90	X-band (8.65-12.33)	>15	<0.50	35	. microstrip probe complementary split ring resonators (CSRRs) has been loaded in the patches to broaden the bandwidth and increase efficiency	. moderate bandwidth . lightweight . low cost . small size . simple processing methods	. Wireless communication, . radar, . remote sensing and . electronic warfare have been operated in microwave and millimeter-wave frequencies
[3] J. Li et al. April 2012	Narrow wall b, side inserted magnetic coupling	WR-28	Ka-band (26-40)	>11	<0.95	33	. Transition utilized a semicircular microstrip ring and stepped impedance transformer.	. compact . simple structure . large size . moderate bandwidth . easy fabrication . drawbacks of huge volume . narrow band . low IL	. They are widely applied in Components and systems of communication, . satellite communication and military appliance (e.g., millimeter wave transmitter/ receiver components, . Front-end of receivers and vector modulators), . radar, remote sensing, . electronic warfare . Microwave measurement.
[4] X. Huang and K.-L. Wu May 2012	Longitudinal inline multi-layered	WR-137	C-band (5.2-8.2)	>15	<0.30	55	Transition consists of an open-circuited microstrip quarter-wavelength resonator and a resonant U-shaped slot on the upper broadside wall of a short-circuited waveguide.	. wide bandwidth . compact in size . convenient for mass production . easy integration multilayer structure . via less . highly compatible with planar circuits	. In commercial and military communication systems operating in microwave and millimeter-wave frequencies
[5] N. Kaneda et al. Dec. 1999	End inserted (inline 90°)	WR-90	X-band (8-12)	>12	<0.30	35	Transition using quasi-Yagi antenna radiator launcher (antenna), consists of two dipole antennas, a truncated ground plane, and a microstrip-CPS balun. The antenna is inserted in the E-plane of the waveguide.	. low insertion loss . moderate bandwidth . small size . low cost fabrication . single layered substrate	. Essential components in many microwave and millimeter-wave application systems
[6] Y. C. Shih et al. 1988	Broadside wall inserted right angled (90°)	WR-28 WR-15 WR-12 WR-10	Ka-band, Q-band, V-band, W-band (26-110)	>15dB	<0.10 (Ka-band), <0.20 (Q-, V-band), <0.35 (W-band)	40	Microstip probe inserted into the broad wall of waveguide through aperture cut and impedance transformer	. simple . compact . low insertion loss . wide bandwidth	. Useful for devices and circuits characterization of MICs and MMICs

[7] W. Grapher et al. Sept. 1994	Broadside wall inserted (90°)	WR-12	E-Band (60-90)	>15	<0.30	10	Slot coupled microstrip antennas radiating into the waveguide	. low bandwidth . compact . small size	. This type of transition is suited for mm-wave system applications for example, in traffic applications.
[8] W. Grabherr and W. Menzel 1992	Broadside wall inserted (90°)	WR-90	X-band (8-12)	>20	<0.50	10-20	. Transitions utilized an aperture coupled patch antenna radiating into the waveguide (planar structures radiating into the waveguide)	. small size, simple . easy of fabrication . low bandwidth . no waveguide parts like a λ/4 short-circuited section are necessary on the top of the substrate	. More suitable for use in the mm-wave range.
[9] F. J. Villegas et al. Jan. 1999	Broadside E-plane right angled (90°)	WR-15 WR-10	Q-band W-band (75-110)	>22 (Q-band), >26 (W-band)	<0.3 (Q-band) <10 (W-band)	10 (Q-band) 8 (W-band)	New design methodology based on iris coupling (Q-band) and Z-cut quartz (W-band)	. a single-layer substrate . new matching topology . new cavity enclosure . hermetic sealing of the interface . low-cost . implementation . more affordable . package-integrable transitions	. Amplifiers and transceivers in military and commercial systems, . especially for millimeter-wave (mm-wave) applications.
[10] Domi-nic Desla-ndes and Ke Wu Feb. 2001	Inline H-plane	WR-28	Ka-band (26-40)	>45	<0.30	12	the microstrip line and rectangular waveguide are fully integrated on the same substrate, and they are interconnected via a simple taper, via holes and metalized grooves	. direct integration . small size . low loss . uses via holes . metalized grooves . low radiation losses due to thin substrate . increase conductor losses due to height of waveguide reduced	. It can be used to integrate passive waveguide components with MIC and MMIC active circuits
[11] Jose M. Pérez-Escudero et al. Sep. 2020	Inline, H-plane cut along length of groove gap RW	WR-10	W-band (75-110)	>15	<0.5	77	. Based on ridge and groove gap waveguides . Transition utilizes a multi-section (each of length λ/4) Chebyshev transformer implemented in groove gap waveguide section	. simpler and easier to manufacture . no microstrip line taper is required . the microstrip substrate does not enter the bed of nails area .wide band width . no need of soldering . uses bed of pin nails	. Uses for sub-millimeter and millimeter frequencies applications
[12] Seema Tomar et al. Dec. 2010	Broadside wall probe insertion through aperture (E-plane)	WR-28	Ka-band (26-40)	>32	<0.70	36	Probe extends from an extension of a printed microstrip circuit (of active and passive circuits) through an aperture in the broad wall of a short-circuited waveguide	. low insertion loss . good return loss . moderate bandwidth . MIC/MMIC compatibility . low cost substrate . vialess . feeding without balun	. The transition is MIC/MMIC compatible
[13] J. H.C. Van Heuven March 1976	End inserted (Inline) E-plane (90°)	WR-42	K-band (18-26)	>26	<0.25	46	The basic idea is the use of gradually tapered ridges at opposite sides of a dielectric substrate, concentrating and rotating the electrical field into a parallel line. . The symmetrical line is matched by a balancing transformer (balun) to the asymmetrical microstrip.	. low reflection . low attenuation . wide band . reproducible performance . sensitive to small variations in the dimensions	. Especially useful at frequencies above 10 GHz.

							An outline of the substrate inserted into the waveguide. The ridges and the ground plane of the microstrip are connected to the wall of the guide along the line length		
[14] Zahid Yaqoob Malik et al. Jan. 2010	End launch, transverse wall (improved right angle transition with amplifica-tion)	WR-62	Ku-band (12-18)	>15	<0.50	9	. Transition had achieved by passing a portion of a microstrip through an aperture in a transverse wall of a waveguide. . Aperture coupled	. no need of waveguide tees or other components . realizable on inexpensive substrates . the assembly directly picks the signal from antenna and provides an amplified signal for down conversion	. It can be used for radar systems, EW systems and compact communication systems.
[15] Sakak -ibara, K et al. 2008	End inserted probe transition (90°)	WR-12	E-band (60-90)	>20	<0.33	32.5	. Transition had developed by applying multi-layer substrate in order to remove the upper back-short waveguide on the substrate. . A probe at one end of the microstrip line is inserted into the waveguide whose one end is short circuited	. multi-layered . uses via holes . flat and planar transition . broad bandwidth . system and cost of millimeter-wave device will gradually decrease	. Millimeter-wave wireless applications, . Automotive radar system (most of cars will equip this), . broadband and Gbit high-speed wireless communication systems whose performance can exceed MIMO and UWB systems in the microwave band, . for connection between waveguide and RF circuit or antenna module.
[16] B.D. Nguyen et al. Dec. 2005	End launch, transverse wall (right angle transition)	WR-10	W-band (75-110)	>23	<0.60	12	E-mode coupling-based transition developed by inserting a small microstripdisk sector antenna inside a standard W-band waveguide	. small compact size . low insertion loss . narrow bandwidth . no need of quarter wave transformer	. Often used for antenna or filter design, .for connecting the different parts of circuits.
[17] Earl R. Murphy et al. June 1984	E-plane (right angle)	WR-10	W-band (75-110)	>23dB	<20	23	Transition is designed by passing a portion of a microstrip circuit through an aperture in a transverse wall of a waveguide	. compact . simple geometry . low loss	Transition suitable for used in millimeter wave circuits.
[18] Ting-Huei Lin, Ruey-Beei Wu 2002	E-plane (90°) end launcher	WR-90 WR-28	X-band (8-12) Ka-band (26-40)	>15dB	<0.70 <1.20	35 40	Transition had utilized a tapered coplanar strip probe and microstrip-to slot line transformer, the transition includes three parts: a microstrip-to-slot line transition circuit, a tapered coplanar strip (CPS) probe inserted into the E-plane of the end of waveguide, and an intermediate section of slot line for impedance matching	. low insertion loss . highly compatible with MIC technology . broad bandwidth . compact size . easy assembly . low fabrication cost	. Play an essential part in specific components like antenna feeds, . high Q filters, . diplexers, . commercial and military systems

[19] Hiedo Ijuka et al. April 2002	E-plane end inserted	WR-12	W-band (75-110)	>40	<0.30	7	E-plane end inserted, uses via-holes for electrical connection between conductor strip and ground through single-layered substrate	. wide bandwidth . low cost, low profile . no waveguide back short . uses via holes . easy fabrication	. The millimeter-wave application for front end module for an automotive radar sensor, . Suitable for connection between mm-wave component such as an antenna, an amplifier and a switch having an interface of a microstrip line or a waveguide.
[20] Yu Lou et al. May 2008	Inline E-plane (90°)	WR-28	Ka-band (26-40)	>40	<0.30	69	Radial shaped probe for field matching and extended ground, notch cut on the strip as impedance matching section	. low insertion loss . compact size . low cost . easy to fabricate printed structure . wideband bandwidth	. Microwave and millimeter circuits or systems
[21] Aliak-barian et al. 2010	End-wall slot coupling, waveguide splitter and three port	WR-15 WR-51 WR-90	Frequencies of design: 18GHz (K- & Ku-band) 60 GHz (V-band) 12 GHz (X-band)	>16 >17 >16	<20 <40 <40	31.5 37.7 35	It consists of an end-wall connection between a simple metal waveguide and a double-sided etched substrate. There is a double slit in the ground of the substrate, coupling the wave to two microstrip ports. Also, two stubs are added to the microstrip line.	. easy manufacturing structure . low cost . small size . less complex . wideband bandwidth . non-tilted pattern	. The transition is applied to a dual band 1 X2 array and Suitable for use in series fed microstrip arrays
[22] R. Shireen et al. 2010	End-wall (inline)	WR-10	W-band (75-110)	>30	<1.15	75	Back-to-back transition uses integrated probe for direct coupling to the WR-10 waveguide with the use of metalled vias on both sides of the microstrip line. probe insertion through inverse T-shaped aperture cut in the broad wall of waveguide	. uses large numbers of vias . wide BW . planar structure	. Widely used for wireless communications, . RADAR sensors and imaging receivers at mm-wave frequencies
[23] Tang, C. et al. Jan. 2020	Inline (90°) transition	WR-28	Ka-band (26-40)	>30	<0.13	48.3	End-wall probe transition using a semicircular loop (impedance transformer), is placed at the E-plane of the rectangular waveguide.	. small size . compact . wider bandwidth . ease to fabricate	. RF-front end at mm-wave frequencies
[24] Ziqiang Tong, Andreas Stelzer May 2012	Vertical transition	WR-10	W-band (75-110)	>20	<0.50	48.5	A differential microstrip patch antenna (DMPA) inside the waveguide acts as a radiation element.	. uses vias holes . compact size and . simple fabrication . allow mass production . wide bandwidth	. Suitable for numerous mm-wave applications
[25] Varshney A. K. Aug. 2013	E-plane probe inserted	WR-28	Ka-band (26-40)	>40	<0.30	38	Impedance transformer based back short transition	. simple . compact . mass production . via-less	. mm-wave receivers and transmitters
[26] Ruei-Ying Fang, and	E-plane broadside wall coupled, Bow-tie	WR-90	*X*-band (8.2–12.4)	>15	<0.30	37.33 & 20.95	Transition using capacitance compensated and transition using quarter-wavelength	. compact . complex structure . broad bandwidth	. mm-wave receivers and transmitters

Chun-Long Wang Sep. 2013	launcher						broad side coupled micrstrip line (BCML), Bow-tie antenna used as power launcher		
[27] Azzemi Ariffin et al. May 2016	Wideband 90° transition	WR-12	E-band (60-90)	>20	<1.41	61.9	Transitions using the radial probe and extended GND planes	. simple probe . wideband bandwidth . uses via-holes	. Broadband ultra-high-speed wireless communication systems such as . Broadband radio links for the backhaul networking of cellular base stations, . Giga wireless LAN, . Gigabit Ethernet networks, . 77GHz automotive RADAR systems and . Inter-vehicle communications
[28] J. M. Pérez April 2016	Inline (0°) transition	WR-10	W-band (75-110)	>19.4	< 0.50	82.5	. Transition operating in the full W-band . Chebyshev multisection (each of length λ/4) transformer . Linear taper transformer in MS line	. simple . compact . mass production . low insertion loss . no soldering is required . wide bandwidth . there is no need to optimize transition parameters	. W-band for applications in different fields as imaging, . communication, . RADAR or automotive RADAR
[29] Azzemi Ariffin, Dino Isa June 2016	Right angled (90°) transition	WR-12	E-band (60-90)	>25	<1.59 <1.45	71.7 (triple-patch probe) 56.4 (single-patch probe)	An optimized ground plane structure on the substrate and a triple-patch probe	. broadband, . uses via holes . simple	. For several ultra-high-data-rate wireless services
[30] Pérez-Escu-dero et al. Sep. 2018	Inline transition	WR-10	W-band (75-110)	>15	<0.63	32	Chebyshev multi-section transformer and microstrip linear taper	. simple . easy to manufacture . planar structure . increases the ease of fabrication and integration . narrow BW	. Imaging , . communications , . RADAR and automotive RADAR
[31] Simone et al. Feb. 2018	Inline end launcher transition	WR-22	Q-band (33–50)	>24	< 0.26	40	. Transition used a section of ridged waveguide and Chebyshev impedance transformer. . A simple small patch matched to the waveguide through a ridged configuration, on which the patch is shorted and a Chebyshev impedance transformer provides the matching from the ridge to the full waveguide. . The impedance match had obtained using a section of ridged waveguide with stepped ridges.	. simple and planar structure . increases the ease of fabrication and the compactness . good return loss . via-less . broad BW	. Q-band (33–50 GHz) receiver of the Sardinia Radio Telescope

[32] Cun Long, Li, et al. Dec. 2019	Inline (0°)	WR-28	Ka-band (26-40)	>13	<0.40	71.43	. employs a circular patch above a wedge-shaped cavity	. low cost . prototype . single-sided PCB . wideband . compact structure and easy integration . high integration density	. Millimeter wave applications
[33] Z. Liu, et al. Jan. 2019	Back-to-back Inline MS line to empty SIW transition	WR-62	Ku-band (12-18)	>21	<0.415	61.67	. Dielectric taper has been eliminated in SIW . Manufactured and designed with different thicknesses of substrates . RO4350B h=0.508mm . RT-duroid 5880 h=0.508 mm . RT-duroid 5880 h=0.254 mm	. broad BW . low attenuation has been achieved by introducing air cut in empty SIW . simple and planar structure . no need of dielectric taper . broad bandwidth	. Successfully applied to design various microwave and millimeterwave passive components, such as filters, phase shifters, directional couplers and horn antenna etc. . Integrate ESIW circuits with active devices such as amplifiers
[34] P. Hügler, et al. Feb. 2020	Inline (0°) H-plane, end inserted differential MSL-to-WG transitions	WR-6	D-band (100-140)	>10	<1.2 <1.8	25	. DMSL to waveguide is built for a mixed multilayer PCB consisting of three substrates with the thicknesses of 127, 254, and 500 µm	. multi-layered PCB . complex design . costly . uses via holes	. Specially applicable at millimetre waves applications . These layers could also be used for digital signals or power planes in the future designs
[35] A. Meyer et al. April 2020	90° broadband stacked-patch transition from microstrip line to circular dielectric waveguide	WC-11	W-band (75-110)	>18	<0.49	28	. A MSL-to-DWG transition with dual-polarized feeding using a stacked patch topology . The stacked patch is inserted into a dielectric stamp at the bottom of the DWG that increases coupling efficiency	. doubles the data rates of interconnects . low space requirement on PCB . no need of additional metallic guiding structures . high coupling efficiency . high IL . poor RL . low cross talk . single layer PCB layout	. Key element for high data rate transmission
[38] R. Gupta, P. P. Kumar Feb. 2020	90° waveguide to coaxial	WR-28	Ka-band (26-40)	>23.4	<0.47	38	. Field matching and Impedance matchings were achieved through ridged waveguide, customized coaxial probe and back-short distance	. compact and light weight . small size . < 1W power handling . improved RF leakage of < -88dBm	. The scope of usability in military and space borne electronic systems

IV. CONCLUSIONS

A detailed study has been carried out on the microstrip line to rectangular waveguide transition from 1967 to September, 2020 and arranged tabulated in terms of their methodology/ technology used, return loss, insertion loss, bandwidth, merits, demerits and their applications. The transitions from almost every band of microwave and millimeter wave have been considered in this work. Therefore, that researcher could easily find out their design band of interest and the research gap in the past historical work. The present study also explains the various technologies to enhancing bandwidth and coupling electromagnetic energy from microstrip line to rectangular waveguide with the use of different types of power launcher and antenna methodologies. All methodology of impedance matching and field matching has been tabulated in the Table I. The development of such transitions is essential and necessary because these transitions are compatible with any kind of planar MMIC/MIC circuitry, active, passive elements, microstrip antennas, filters, radar sensors, wireless 5G and above MIMO and massive MIMO antennas for enhancing their speed. The use of waveguide makes these transitions to easily connect waveguide horn antenna to receive and transmit power from or to a planar microstrip circuit at millimeter and microwave range. The most find applications where these transitions are utilized are military, commercial, wireless transmitter and receiver, radar sensors, radio astronomy, microwave imaging, automotive radar, several ultra-high data rate wireless services, Giga wireless LAN, Gigabit Ethernet networks, RF-front end at mm-wave frequencies, play an essential part like antenna feeds and high Q-filters and diplexer, automatic start Vehicles.

V. Recommendation

The tabularized comparison conclude that mostly work have been carried out in the X-band, Ku-band, Ka-band and very few designs works is available in the Q-band, V-band, W-band, D-band, E-band and mm-waves. Therefore, work can be carried out in these bands. In these bands transitions design to achieve low value of insertion loss, good return loss i.e. VSWR near to 1, field matching and impedance matching to achieve enhanced fractional bandwidth and coupling efficiencyare the big challenges. These results can be acquired by the use of new design methodology and techniques like the use of magnetic coupling, loop probe insertion, modified ground, fractal antennas, metamaterial structures (CSRR, SSRR, etc). These designed transitions will be utilized in RADAR, very high data rate wireless communications, satellite communication, digital plane space borne and ship borne, military and commercial applications as connector,front end RF element, amplifier, filters, transmitters and receivers systems.

Acknowledgment

The authors would like to thank our vice-chancellor, Dean FET and Head of the department of Electronics and Communication as well as Microwave LAB and their supporting staff, FET, Gurukula Kangri Vishwavidyalaya, Haridwar, India for providing the simulation environment of Ansoft HFSS and the measurement instruments.

References

[1] S E. Hassan, M. Berggren, B. Scheiner, F. Michler, R. Weigel and F. Lurz, "Design of Planar Microstrip-to-Waveguide Transitions Using Topology Optimization", *IEEE Radio and Wireless Symposium (RWS)*, Orlando, FL, USA, 16 May 2019, pp. 1-3, DOI: 10.1109/RWS.2019.8714566

[2] Y. Ren, K. Li, F. Wang, B. Gao, and H. Wu, "A Broadband Magnetic Coupling Microstrip to Waveguide Transition Using Complementary Split Ring Resonators", *IEEE Access*, vol. 7, pp. 17347-17353, 2019, DOI:10.1109/ACCESS.2019.2895159

[3] J. Li, J. Xu, and J. Fu, "A full Ka-band Microstrip-to-Waveguide Transition Using Side-Inserted Magnetic Coupling Semicircular Ring", *Proc. IEEE Wireless Microw. Technol. Conf. (WAMICON)*, Apr. 2012, pp. 1-6. DOI: 10.1109/WAMICON.2012.6208434

[4] X. Huang, and K.-L. Wu, "A Broadband U-slot Coupled Microstrip-to-Waveguide Transition", *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 5, pp. 1210-1217, May 2012, DOI: 10.1109/TMTT.2012.2187677

[5] N. Kaneda, Y. Qian, and T. Itoh, "A Broad-Band Microstrip-to-Waveguide Transition Using Quasi-YagiAntenna", *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 12, pp. 2562-2567, Dec. 1999, DOI: 10.1109/22.809007

[6] Y. C. Shih, T. N. Ton, and L. Q. Bui, "Waveguide-to-Microstrip Transitions for mm-wave Applications", *IEEE MTT-S Int. Symp. Dig.*, vol. 1, New York, 1988, pp. 473-475.

[7] W. Grapher, B. Hudler, and W. Menzel, "Microstrip to Waveguide Transition Compatible with MM-wave Integrated Circuits", *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1842-1843, September 1994.

[8] W. Grabherr, and W. Menzel, "A new Transition from Microstrip Line to Rectangular Wave-Guide", *22nd European Microwave Conference*, 1992, Helsinki, Finland, pp. 1170-1175.

[9] F. J. Villegas, D. I. Stones, and H. A. Hung, "A Novel Waveguide-to-Microstrip Transition for Millimeter-wave Module Applications", *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 48-55, January 1999.

[10] D. Deslandes, and K. Wu, "Integrated Microstrip and Rectangular Waveguide in Planar Form", *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 2, February 2001.

[11] J. M. Pérez-Escudero, A. E. Torres-García, R. Gonzalo, and I. Ederra, "A Gap Waveguide-Based Compact Rectangular Waveguide to a Packaged Microstrip Inline Transition", *Applied Sciences*, vol. 10, no. 14, Article 4979, Sep. 2020, DOI: 10.3390/app10144979

[12] S. Tomar, S. Kumar Singh, L. Suthar, R. B. Singh, and A. Kumar, "E-Plane Waveguide to Microstrip Transition for Wave Applications", *ICMARS 2010*, December 2010.

[13] J. H.C. Van Heuven, "A New Integrated Waveguide-Microstrip Transition", *IEEE Transactions on Microwave Theory and Techniques*, March 1976.

[14] Z. Y. Malik, M. I. Nawaz, and M. Kashif, "MMIC/MIC Compatible Planar Microstrip to Waveguide Transition at Ku-band for Radar Applications", *International Bhurban Conference on Applied Sciences & Technology*, Islamabad, Pakistan, 11-14 January, 2010, pp. 51-53.

[15] K. Sakakibara, M. Hirono, N. Kikuma, and H. Hirayama, "Broadband and Planar Microstrip-to-Waveguide Transitions in mm-wave Band",*International Conference on Microwave and Wave Technology 2008*, DOI: 10.1109/icmmt.2008.4540667

[16] B. D. Nguyen, C. Migliaccio, Ch. Pichot, and N. Rolland, "Design of Microstrip to Waveguide Transition in the W-Band Suitable Antenna or Integrated Circuits Connections", *Microwave and Optical Technology Letters*, vol. 47, no. 6, December 20, 2005, pp. 518-520, DOI: 10.1002/mop.21216

[17] E. R. Murphy, *Microstrip to Waveguide Transition*, U.S. Patent, 4453142, June 1984.

[18] T.-H. Lin, and R.-B. Wu, "A Broadband Microstrip-to-Waveguide Transition with Tapered CPS Probe", *2002 32nd European Microwave Conference*, Milan, Italy, September 23-26, 2002, DOI: 10.1109/EUMA.2002.339360

[19] H. Ijuka, T. Watanabe, K. Sato, and K. Nishikawa, "Millimeter-wave Microstrip Line to Waveguide Transition Fabricated on a Single Layer Dielectric Substrate", *R&D Review of Toyota*, CRDL, vol. 37, no. 2, Research report received on 23, April, 2002.

[20] Y. Lou, C. H. Chan, and Q. Xue, "An In-line Waveguide-to-Microstrip Transition Using Radial-Shaped Probe", *IEEE Microwave and Wireless Components Letters*, vol. 18, no. 5, May 2008, pp. 311-313, DOI: 10.1109/LMWC.2008.922114

[21] H. Aliakbarian, A. Enayati, G. A.E. Vandenbosch, and W. De Raedt, "Novel Low-Cost End-Wall Microstrip-To-Waveguide Splitter Transition", *Progress in Electromagnetics Research*, 2010, 101, pp. 75-96. DOI:10.2528/pier 09081805

[22] R. Shireen, S. Shi, and D. W. Prather, "W-band Microstrip-to-Waveguide Transition Using via Fences", *Progress in Electromagnetics Research Letters*, vol. 16, pp. 151-160, August 2010.

[23] C. Tang, X. Pan, F. Cheng, and X. Lin, "A Broadband Microstrip-to-Waveguide End-wall Probe Transition and its Application in Waveguide Termination", *Progress in Electromagnetics Research Letters*, January 2020, vol. 89, pp. 99-104, DOI: 10.2528/pierl19110601

[24] Z. Tong, and A. Stelzer, “A Vertical Transition between Rectangular Waveguide and Coupled Microstrip Lines”, *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 5, May 2012, pp. 251-253.

[25] A. K. Varshney, “A Microwave Rectangular Waveguide-to-Micro-strip line Transitions @30 GHz”, *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, no. 8, August 2013.

[26] R.-Y. Fang, and C.-L. Wang, “Miniaturized Microstrip-to-Waveguide Transition using Capacitance-Compensated Broadside-Coupled Microstrip Line”, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 3, no. 9, September 2013, DOI: 10.1109/TCPMT.2013.2244644

[27] A. Ariffin, D. Isa, and A. Malekmohammadi, “Broadband Transition from Microstrip Line to Waveguide using a Radial Probe and Extended GND Planes for Millimeter-Wave Applications”, *Progress in Electromagnetics Research Letters*, vol. 60, pp. 95-100, May 26, 2016.

[28] J. M. Pérez, A. Rebollo, R. Gonzalo, and I. Ederra, “An Inline Microstrip-to-waveguide Transition Operating in the full W-Band based on a Chebyshev Multisection Transformer”, *2016 10th European Conference on Antennas and Propagation (EuCAP)*, Davos, pp. 1-4, April 2016, DOI: 10.1109/ EuCAP.2016.7481796

[29] A. Ariffin, and D. Isa, “Bandwidth Enhancement of Microstripline-to-Waveguide Transitions for Broadband E-band Module Applications”, *Microwave and Optical Technology Letters*, vol. 58, no. 6, June 2016, pp. 1398-1401, DOI: 10.1002/mop.29836

[30] J. M. Pérez-Escudero, A. E. Torres-García, R. Gonzalo, and I. Ederra, “A Simplified Design Inline Microstrip-to-Waveguide Transition”, *Electronics*, 2018, vol. 7, no. 10, Article 215, DOI: 10.3390/electronics7100215

[31] M. Simone, A. Fanti, G. Valente, G. Montisci, R. Ghiani, and G. Mazzarella, “A Compact In-line Waveguide-to-Microstrip Transition in the Q-Band for Radio Astronomy Applications”, *Electronics*, February 2018, vol. 7, no. 2, Article 24, DOI: 10.3390/electronics7020024

[32] C. L. Li, C. Jin, H. Q. Ma, and X. W. Shi, “An Inline Waveguide-to-Microstrip Transition for Wideband Millimeter-wave Applications”, *Microwave and Optical Technology Letters*, pp. 1-5, December 2019, DOI: 10.1002/mop.32199

[33] Z. Liu, J. Xu, and W. Wang, “Wideband Transition From Microstrip Line-to-Empty Substrate-Integrated Waveguide Without Sharp Dielectric Taper”, *IEEE Microwave and Wireless Components Letters*, vol. 29, no. 1, pp. 20-22, January 2019, DOI: 10.1109/LMWC.2018.2881055

[34] P. Hügler, T. Chaloun, and C. Waldschmidt, “A Wideband Differential Microstrip-to-Waveguide Transition for Multilayer PCBs at 120 GHz”, *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 2, pp. 170-172, February 2020, DOI: 10.1109/LMWC.2019.2958208

[35] A. Meyer, S. Karau, and M. Schneider, "Broadband Stacked-Patch Transition from Microstrip Line to Circular Dielectric Waveguide for Dual-Polarized Applications at W-Band Frequencies," *2019 49th European Microwave Conference (EuMC)*, Paris, France, published online 27, April 2020, pp. 440-443, DOI: 10.23919/EuMC.2019.8910938

[36] D. M. Pozar, *Microwave Engineering*, Wiley Student edition, 4th edition, pp. 148-149, reprint 2016.

[37] S. Y. Liao, *Microwave Devices and Circuits*, Pearson Prentice Hall, 3rd edition, 2007.

[38] R. Gupta, and P. P. Kumar, “Improved Design of Ka-band Waveguide to Coaxial Right Angle Microwave Transition”, *URSI RCRS 2020*, IIT (BHU), Varanasi, India, 12-14 February 2020, DOI: 10.23919/URSIRCRS49211.2020.9113526