CHAPTER 2

LITERATURE REVIEW

Mode converters are the passive two port microwave device used to convert RF wave propagating from the mode appearing at its input port to another desired mode coming out from its output port. In general microwave generator or source emits radiation in one specific mode. To use such generated mode in different application mode transformation or conversion is required. For converting generated mode to required modes, a mode converter is designed and place in between source and radiator (or application unit). High power microwave system depends on mode converter having a low reflection, high efficiency, and sustainable device at high temperature and high electric field. Mode converter can be classified into three types [Quine (1968)].

- Mode converter using Abrupt discontinuity
- Mode converter using Gradual discontinuity
- Mode converter using Axial discontinuity

2.1 Mode converter using Abrupt discontinuity

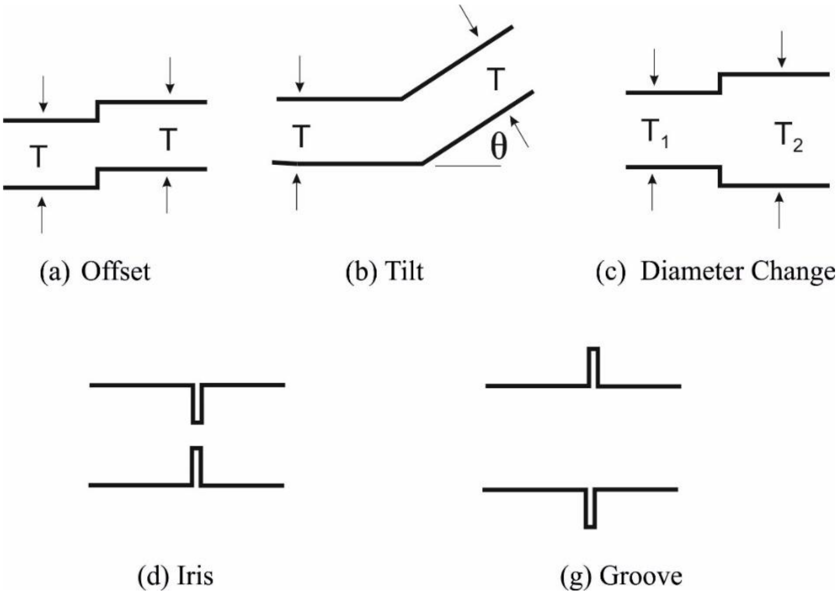

Figure 2.1. Waveguides with abrupt discontinuity

Change in a cross-sectional area, like, abrupt offset, tilt, diameter change, iris, and grove results in the spurious signal [Quine (1968)]. Waveguide interruption is known to induce coupling between modes. When oversize waveguides are employed, losses can occur as a result of the conversion of energy from the propagating mode to other desired mode. Any departure from the perfect cylindrical or rectangular geometry causes coupling among the cylindrical waveguide modes and results in mode conversion losses. Some of the discrete change in the cross-sectional area of the waveguide is shown in Figure 2.1.

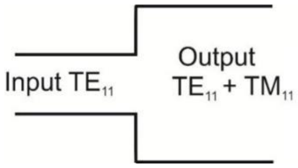

Figure 2.2. TE_{11} to $TE_{11} + TM_{11}$ mode conversion through abrupt discontinuities conductor

The mode converter based on abrupt changes usually works on reflection and excitation of higher or lower order modes. For instance, when apertures of a rectangular or cylindrical waveguide change, there is higher order modes and reflections generated. In Figure 2.2, abrupt change in the aperture occurs due to connection with overmoded waveguide which supports TE_{11} along with TM_{11} mode.

2.2 Mode Converter using Gradual Discontinuity

If there is any change or a discontinuity in the geometry of waveguide, it will cause a local change in its RF field distribution; this may result in the generation of new modes depending upon the structure and input mode [Quine (1968)]. In Figure 2.3, schematic diagrams of mode converters based on gradual discontinuity are shown. Away from the bend, some new modes disappear or attenuate out. Offset bends, serpentine structures, departure of perfect circular to the rectangular waveguide or perfect rectangular to the circular waveguide, and tapered waveguides are examples of gradual discontinuities.

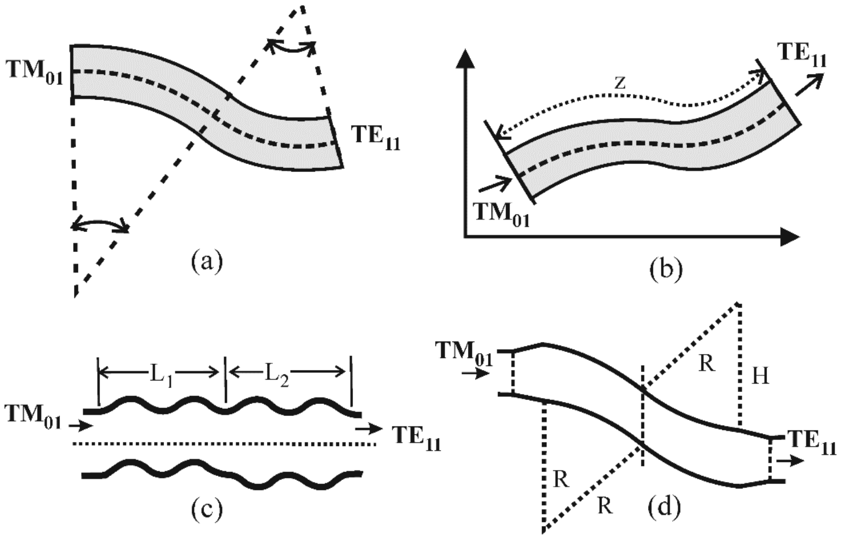

Figure 2.3. Gradual discontinuity; schematic mode converters of (a) Yang *et al.* (1995), (b) Ling and Zhou (2001), (c) Yang *et al.* (1997), (d) Lee *et al.* (2004).

For mode conversion of TM_{01} mode to TE_{11} mode, Yang *et al.* (1995) had reported the mode converters design having conversion efficiency more than 97% at operating frequency 35 GHz, and the Ling and Zhou (2001) had reported the conversion efficiency more than 99% at 4 GHz. Also, Yang *et al.* (1995) had reported the mode converter design having conversion efficiency 94.5% at operating frequency 35 GHz and Lee *et al.* (2004) design had conversion efficiency 95.6% for frequency 10 GHz. All these mode converter design gives good mode conversion efficiency but the fabrication with precision and to achieve compactness in HPM system becomes a challenge.

2.3 Mode converter using Axial discontinuity

Axial discontinuities in the standard waveguides are also used for obtaining the mode conversion, either by deformation in the outer or inner conductor of the coaxial waveguide; or by inserting metallic plates in the coaxial waveguide to form sectoral waveguide (SWG). The SWG mode converter is popular for rearranging the modal field parts of a coaxial waveguide for mode conversion of *TEM* to TE_{11} mode. The literature review is focused on axial discontinuity in mode converter, as it is capable of handling high powers and low loss.

Using axial radial metallic plates, it is possible to transform coaxial waveguide in SWGs. As shown in Figure 2.4, Somov *et al.* (1998) have investigated the SWG mode converter having the capability to convert coaxial waveguide *TEM* to TE_{11} mode of a circular waveguide. In this design coaxial waveguide has been divided into four SWGs. Here the coaxial waveguide guide is azimuthally divided using four axial radial metallic plates, placed at angles 0, π, $4\pi/3$ and $5\pi/3$ rad, thus forming one SWG of sectoral angles π rad and three SWGs of sectoral angles $\pi/3$ rad, respectively. Hence at the end of the sectoral region, results in π rad phase difference between SWG_{π} and $SWG_{\pi/3}$ causes mode conversion. The design was reported; however, the conversion efficiency and frequency of operation were not reported.

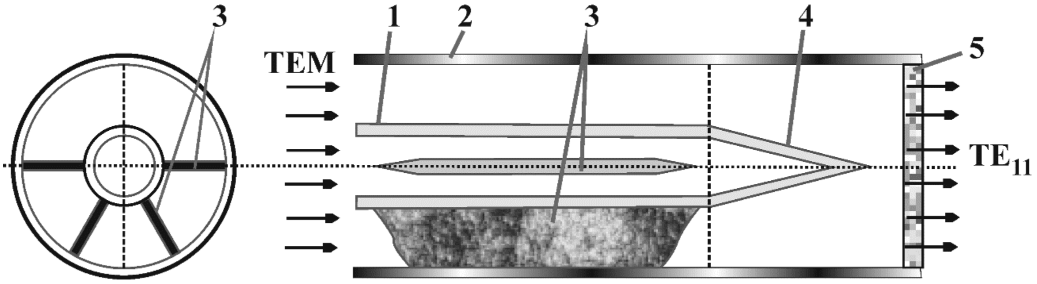

Figure 2.4. Schematic of SWG mode converter, reported by Somov *et al.* (1998), having one SWG_{π} and three $SWG_{\pi/3}$; 1 - inner conductor of the coaxial waveguide, 2 - the outer conductor of the coaxial waveguide, 3 - longitudinal and radial diaphragm separating the waveguide into sectors, 4 - conical aligner section of the radiator, 5 - dielectric window for the emission output.

As shown in Figure 2.5, Yuan *et al.* (2005) have divided coaxial waveguide in four sectors using sector plates of different lengths. First, the coaxial waveguide was separated in four $SWG_{\pi/2}$. Two plates having same length was used to keep separating upper and lower semi-circle. Then, one upper plate end and create one π rad and two $\pi/2$ rad SWGs. Hence, at the end of the sectoral region, results in π rad phase difference between SWG_{π} and $SWG_{\pi/2}$ causes mode conversion. Also, the insufficient return loss has been reported, and this drawback has overcome by using stub matching. In this design conversion efficiency was reported as 98.5% at frequency 1.9 GHz [Yuan *et al.*

(2005)], in addition, conversion efficiency exceeds 90% for the device bandwidth of 10%. Also, Kumar *el al.* (2017) had reported limitation of choosing different sectoral angle combination to form SWG mode converter. Figure 2.6, shows the different combination compared by Kumar *el al.* (2017).

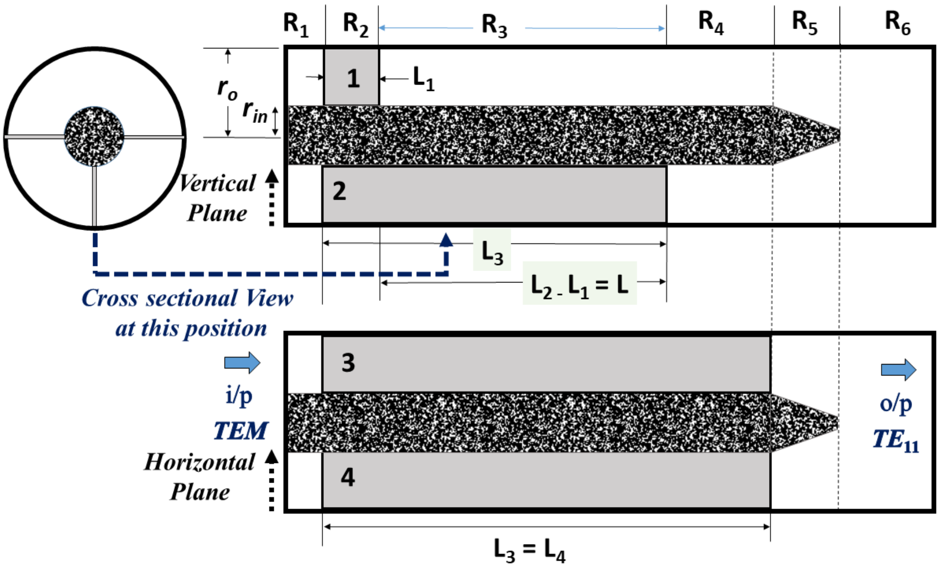

Figure 2.5. Structure of the novel mode converter reported by Yuan *et al.* (2005). Left: Axial view of SWG mode converter in vertical plane and horizontal plane, Right: front view displaying four SWGs.

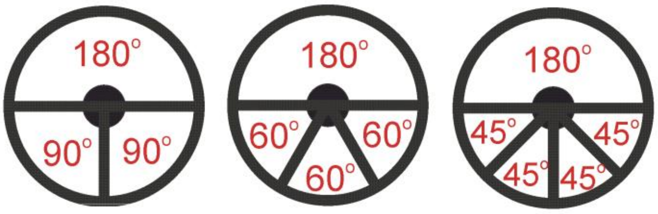

Figure 2.6. Cross sectional view of different combination of SWGs to form mode converter.

Dielectric material introduces phase delay, so applying dielectric material of specific length in the lower half of coaxial waveguide can create mode conversion at the output. The various dielectric materials have different permittivity as well as attenuations. So, in this mode converter dielectric material property has a major effect on the device mode conversion efficiency. Figure 2.7, shows a dielectric mode converter reported by Chittora *et al.* (2015). The conversion efficiency was reported 99.5% using dielectric material PTFE near 3.1 GHz frequency, with a maximum electric field strength of 114 kV/cm on the metal surface.

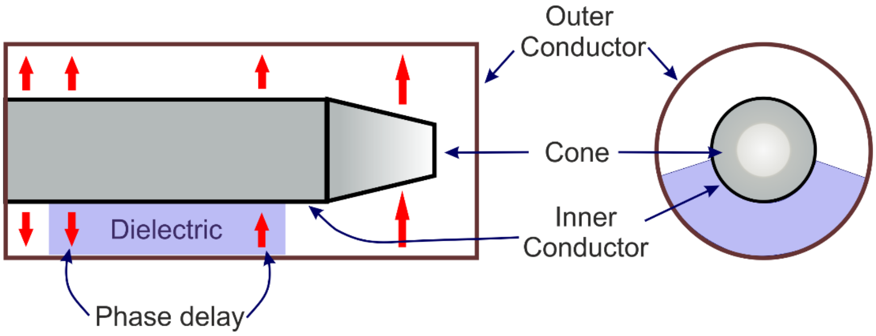

Figure 2.7. Dielectric loaded SWG mode converters design, by Chittora *et al.* (2015).

Metallic photonic bandgap (PBG) mode converter – PBG metallic material has some relative permittivity. PBG metals are having low imaginary value and negative real value of conductivity. If metallic rods of the PBG structure placed in a periodic manner, then it can introduce phase delay in electromagnetic wave propagating in specific frequency band. As shown in Figure 2.8, during the wave propagation through PBG metallic rods, phase delay occurs and introduces mode conversion at the output [Wang *et al.* (2015)]. Their results show the mode converter efficiency 99% at the centre frequency 1.58 GHz.

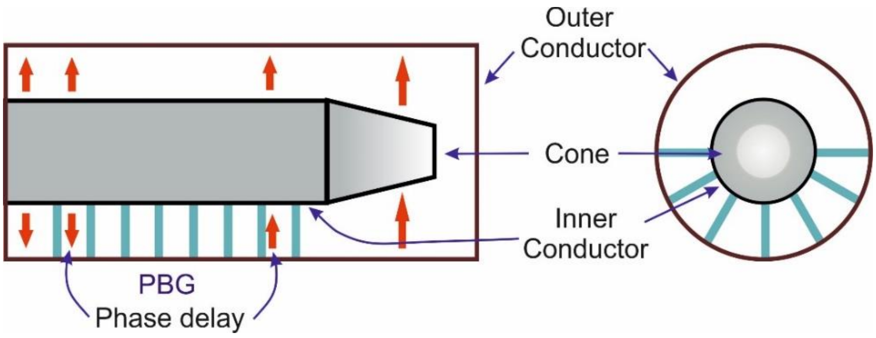

Figure 2.8. Metallic photonic loaded SWG mode converter design, by Wang *et al.* (2015).

Yuan *et al.* (2006) had reported mode converter where phase shift for mode conversion as well as polarisation shift has been created as shown in Figure 2.9. It is having input circular waveguide transitioned into a coaxial waveguide with up tapering.

Using eight metal plates, loaded in the coaxial waveguide separating it into eight SWGs each of angular separation $\pi/4$. The four plates marked with zero are uniform with a length of L_0. The other four plate's length marked with L_1, L_2, L_3, and L_4. At the end of plates (1, 2, 3, and 4), two adjacent $SWG_{\pi/4}$ are combined to form one $SWG_{\pi/2}$. The matching rods introduce to compensate the reflections from the rear edges of plates 1–4, respectively. Before the ends of plate 0, the inner and outer radius of the converter is reduced using down tapering. Using plate 1 to 4 length, in clockwise (or in anti-clockwise) direction, the phase shift of $\pi/2$ rad is applied additive according to quadrant. So, in e.g. if the first quadrant has zero phase shift, then the second quadrant have $\pi/2$ rad phase shift, the third quadrant have π rad phase shift and the fourth quadrant have $3\pi/2$ rad phase shift. Using this technique this design can provide mode conversion along with circular polarisation (CP). The conversion efficiency of TM_{01}-TE_{11} CP SWG Mode converter is 99% at the frequency 4GHz. This design contains various tapered structure along with tapered SWGs. The tapered structures for the outer wall of coaxial waveguide requires lots of optimization as well weight of the mode converter also increases.

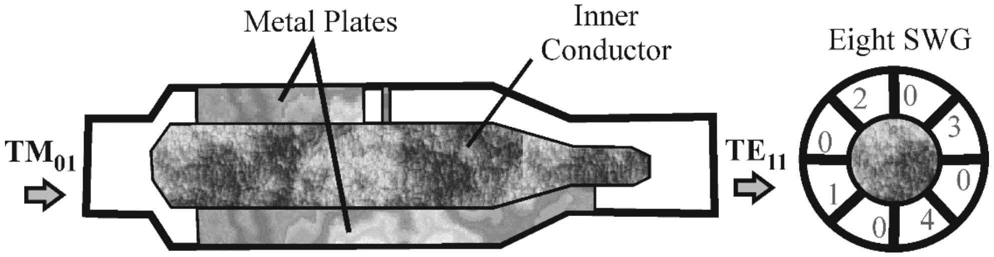

Figure 2.9. Schematic of the novel Circular Polarization mode converter developed by Yuan *et al.* (2006).

The design reported by Eisenhart used a shorted inner conductor [Eisenhart (1998)]. Here mode conversion is achieved by eliminating the lower semicircle fields' content and transforming coaxial rectangular waveguide in a conventional rectangular waveguide, shown in Figure 2.10. This design idea supports the transformation of *TEM* mode to TE_{11} mode using a shorted inner conductor with an outer wall of the waveguide. The drawback of this design is low conversion efficiency. The reported design was for L-band with insertion loss 0.25 dB; so, the conversion efficiency lower than 94.4%.

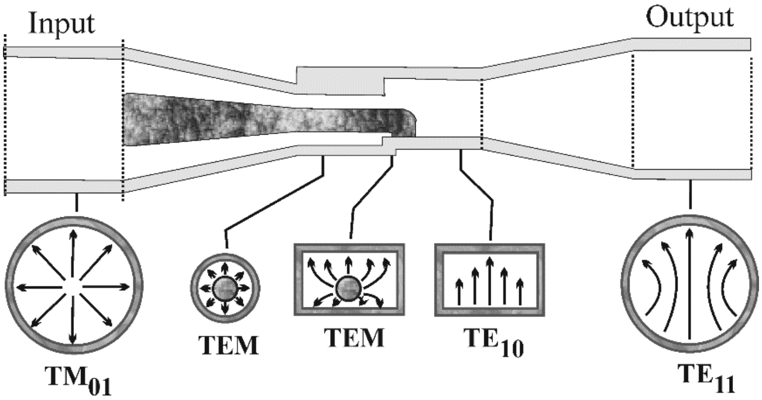

Figure 2.10. Schematic Eisenhart (1998).

A mode converter similar to Eisenhart (1998) design were reported by Tribak *et al.* (2013) were design with up-planar steps of inner conductor at the input end and down-planar steps of inner conductor at the shorted end, as shown in Figure 2.11. It has used planar step discontinuities for impedance matching according to the characteristic impedance of relevant mode and having higher mode conversion efficiency; however, design and development of such a mode converter is complex. The reported mode converter design in Ku-band had conversion efficiency 98.8%.

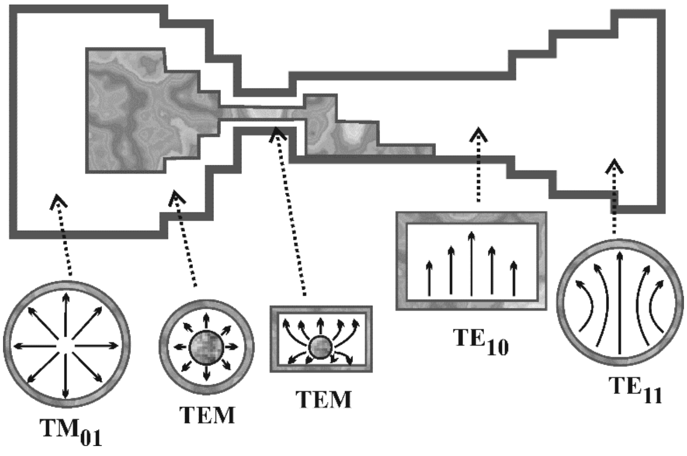

Figure 2.11. Schematic mode converters design by Tribak *et al.* (2013).

Folded SWGs mode converter with up-tapered radial disturbance has been reported by Wang *et al.* (2013), shown in Figure 2.12. A pair of folded $SWG_{\pi/2}$ are placed in an upper semicircle, and the lower semicircle is disturbance free SWG_{π}. Thus, the folded $SWG_{\pi/2}$ introduces π rad phase difference with the SWG_{π}, to perform the mode conversion. This folded SWG mode converter was designed for L-band MILO. The similar mode converter design concept was also reported by Zang *et al.* (2015), now for circular polarization, as shown in Figure 2.13. Zang *et al.* (2015) design contain four SWG where three are folded with different height of disturbance. Here clockwise or anticlockwise delay of $\pi/2$, π and $3\pi/2$ rad in phase results in mode conversion with circular polarization. The conversion efficiency reported was more than 99% having compact device structure.

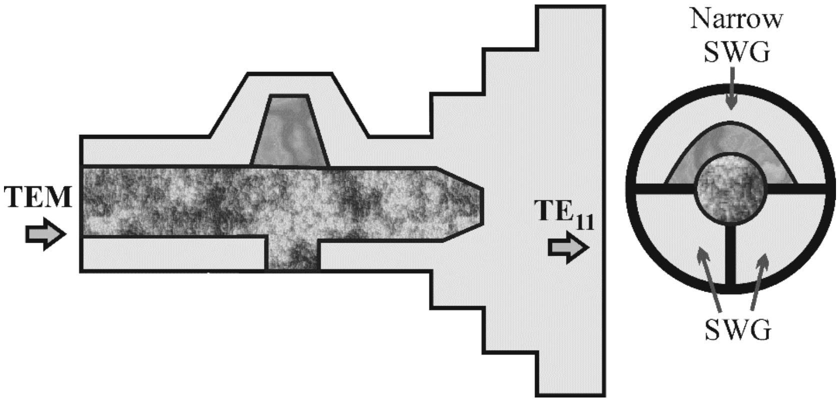

Figure 2.12. Schematic of folded SWG mode converters by Wang *et al.* (2013)

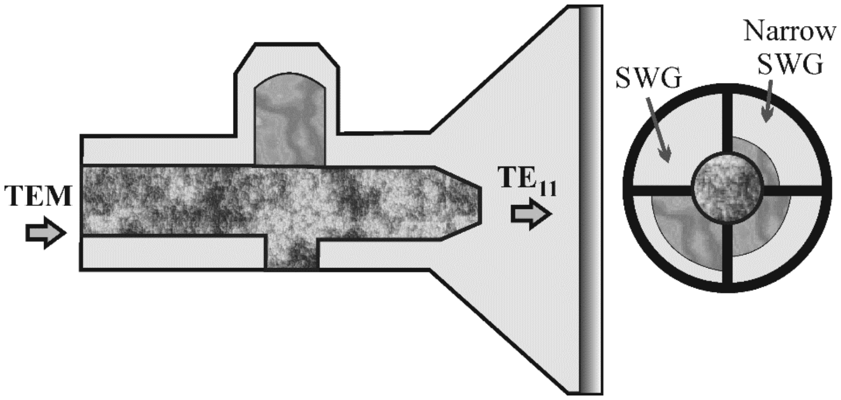

Figure 2.13. Schematic circularly polarized mode converters by Zang *et al.* (2015)

Some of the researches done on mode conversion externally by using dielectrics but the is drawback of breakdown of electromagnetic field [Baum and Courtney (1966), Baum (1967) and Courtney (2004)] and burn of such dielectric material could occur. The current state-of-the-art research in SWG mode converter has been focused in many directions. Primarily, the focus is on realizing high power capabilities, conversion efficiency with high return loss, beam stability. They should be easier to design, lower in weight and of compact size.

2.4 Problem Definition

The major problem with mode converter design based on abrupt discontinuity and gradual discontinuity is that they are complex to design. Since the literature is focused on a survey of mode conversion of TM_{01} mode to TE_{11} mode, the mode converters having gradual discontinuity found low conversion efficiency. The SWG mode converters can produce good efficiency, all metal structure and compact design. Beam stability is also an important characteristic of the mode converters, and only Chittora *et al.* (2015) had discussed this characteristic. However, this design was loaded with dielectric to achieve the desired mode conversion whereas dielectrics are not sustainable for the mode converters of high power applications. Although folded SWG mode converters are good in compactness whereas designing is very complex. The other reported mode converters are based on the axial discontinuities and are complex in design and development as well as heavier in weight. So, the all metal SWG mode converter requires focus on study of beam stability, characterization using computational analysis and design study for lighter-weight mode converter.