Low-Loss Transmission Line for a 3.4-kW, 93-GHz Gyro-Traveling-Wave Amplifier

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***Abstract*— In this article, a transmission line system for the propagation of millimeter-wave radiation is presented. The full system includes a TE_{11}-to-TE_{01} mode converter, waveguide tapers, miter bends, and many straight sections. The design of each of these components is described, and the optimized simulation results are given. The mode converter shows a greater than 96% mode conversion efficiency that can be achieved over a 2% bandwidth at the *W*-band. The miter bends demonstrate a transmission loss of 0.04 dB each over the same bandwidth when they are configured to introduce a mixture of higher order waveguide modes before the reflecting surface. An example transmission line system with a propagation length of 20 m, inclusive of four 90° bends with an oxygen-free high conductivity (OFHC) copper waveguide material, was studied over a 90–96-GHz frequency range and showed a 0.84-dB transmission loss at 93 GHz.**

***Index Terms*— Gyro-traveling-wave tube, miter bend, mode converter, transmission line.**

I. Introduction

MILLIMETER-WAVE (MMW) radiation in W-band, at the kilowatt power level, is desirable for a number of applications. With electron paramagnetic resonance (EPR), the increased peak MMW power improves spatial resolution and shortens the imaging times [1]. Nuclear fusion research experiments require quasi-continuous wave (CW) MMW sources at multimegawatt level power to heat a fusion plasma [2]. The sources for these applications must often be sited a significant distance from the point of use. The physical size of the source, electronic noise from high-voltage power supplies, and stray magnetic fields are all reasons to locate the source some distance from the point of application. Transmitting the radiation to the point of use with low insertion loss while maintaining the correct mode pattern becomes an important issue.

Propagating the MMW in free space is the simplest solution; however, the transmitting apertures must be large in order to control losses due to diffraction. Therefore, maintaining a propagating mode in a metallic waveguide structure is a more practical method. The TE_{01} mode in a circular waveguide and the HE_{11} mode in a corrugated waveguide [3]–[5] are suitable options with attractive properties, such as a centrally located wave power within the waveguide, which reduces the field strength at the waveguide wall and minimizes the conduction losses. It is also possible to couple to either mode with low insertion loss. The HE_{11} mode allows propagation in linear or circular polarization, has a quasi-optical far-field radiation pattern useful for many applications, and shows broad operational bandwidth (example, 100–160 GHz for application in the International Thermonuclear Experimental Reactor (ITER) [6]). The HE_{11} transmission line has been widely used in plasma fusion and dynamic nuclear polarization (DNP) systems [7]; however, the corrugated waveguide is relatively complicated and expensive to manufacture, especially at higher operating frequencies where dimensions become smaller and tolerances tighter. The TE_{01} mode also has a symmetric, and centrally located, electric field with low loss, yet it propagates in a smooth circular waveguide. An argument can be made that lower manufacturing costs and more robust accommodation of manufacturing tolerances support the use of TE_{01} transmission systems.

The proposed transmission line system includes: 1) a mode converter to convert output mode of the source into propagating mode of the transmission line system; 2) waveguide tapers to match waveguide diameters; 3) waveguide bends to allow for directional changes; and 4) straight waveguide sections with low loss.

A miter bend can introduce mode conversion and thereby loss of power in the desired modes. In 1993, it was proposed that these negative effects could be significantly reduced through the conversion of incoming mode (TE_{01}) to higher order TE_{0n} modes [8]. The improved design, incorporating a mode converter, was measured at W-band frequencies (93–98 GHz) [9]. Further work at Ka-band focused on a transmission line system with a mode converter (TE_{11}–TE_{01})

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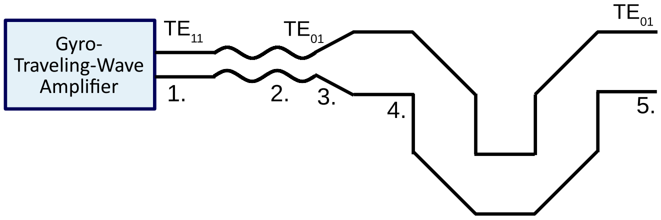


Fig. 1. Transmission system showing: 1) circular waveguide with TE_{11} mode; 2) TE_{11}-to-TE_{01} mode converter; 3) linear taper; 4) miter bends; and 5) output to application.

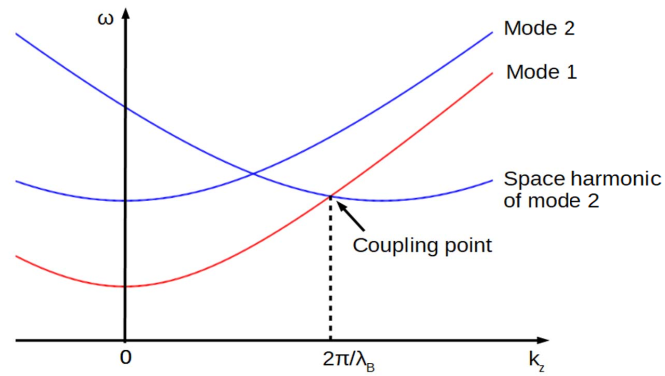
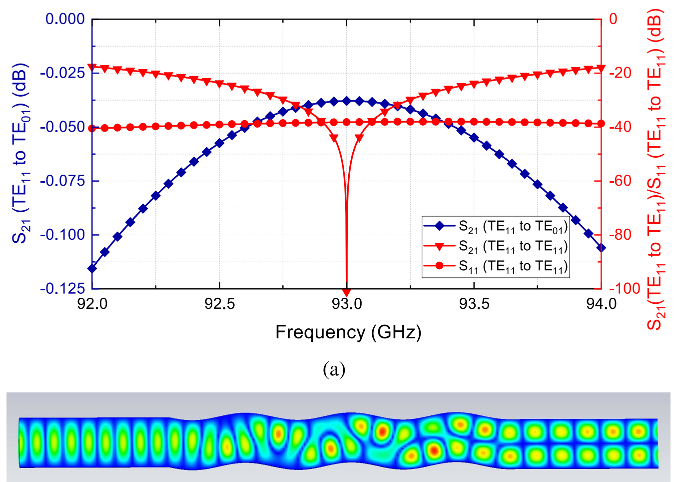


Fig. 2. Dispersion curves of the coupling modes.



(a)

(b)

Fig. 3. (a) Scattering parameters of the mode converter. (b) Field pattern inside the mode converter at the center frequency.

and a series of the improved miter bends [10]. A significant reduction in the transmission loss of 15 times was achieved compared with the conventional miter bend. This approach has also been utilized in applications, such as the resonant ring for the testing of components with high-power microwaves [11]. A design of miter bend with a TE_{03}-mode dominant, with a weaker mixture of TE_{04} and TE_{02} modes, has been used for overmoded gyrotrons [8].

This article presents a 20-m ($6250\lambda_0$) long transmission line system for an application where the source is sited away from the load or antenna or point of use. This article is organized as follows. The design of the mode converter, waveguide taper and miter bend, is presented in detail. A transmission line system suitable for a W-band gyrotron traveling-wave amplifier (gyro-TWA) [12], [13] with circularly polarized TE_{11} output is presented.

II. Components in a Transmission Line System

The general scheme of the transmission line system is shown in Fig. 1. The output from the MMW radiation source is transmitted some distance to the end application through this system. Four miter bends are included in the proposed system to show the flexibility of the system, for example, where obstructions prevent a direct transmission path, as often occurs in complex systems.

A. Mode Converter

Mode converters of many forms can be designed depending on the characteristics of the desired input and output modes [14]–[16]. Even for the same conversion (for example, the TE_{11}-to-TE_{01} mode in the circular waveguide), there are different ways to realize the mode converter [17], [18].

In this article, a mode conversion approach based on a mode-coupling theory is used. The surface profile of such a mode converter has the following expression in the cylindrical coordinates [19]:

$$R(z,\theta) = R_0 + \varepsilon R_0 \cos(2\pi z/\lambda_B)\ \cos(m_B\theta) \tag{1}$$

where R_0 is the average radius, ε is the maximum corrugation amplitude deviation from the average radius, λ_B is the beat wavelength, and m_B is the periodicity in the azimuthal direction. The mode conversion can be examined from the dispersion curves of the incident mode (mode 1) and the spatial harmonic of the output mode (mode 2) (see Fig. 2). At the intersection point, where the Bragg resonance conditions are satisfied, the two modes have strong coupling and can convert the energy of the input mode into the output mode [20]. Theoretically, this kind of mode converter is able to achieve mode coupling between any two modes.

To convert TE_{11} mode into TE_{01} mode at a center frequency of 93 GHz, the initial geometry parameters of the beatwave mode converter can be derived from the mode coupling equation based on the perturbation theory [21]–[23]. This yields a first-pass design, which can then be optimized to meet the requirements for coupling coefficient or bandwidth. For example, reducing ε results in a longer structure with larger bandwidth. Fig. 3 shows the simulation results with the geometry parameters, $R_0 = 2.50$ mm, $\varepsilon = 0.15$, $\lambda_B = 10.65$ mm, and the overall length 34.30 mm. The central frequency mode conversion is 99.1%, while at the top and tail of the 2% passband, the conversion is 98.0% and 96.9%, respectively.

The length of the mode converter and its effect on the mode conversion efficiency was investigated, data shown in Fig. 4. It is seen that with the higher number of beat wavelengths, the bandwidth reduces, and however, the central mode conversion increases. Therefore, the choice of length will be a tradeoff between the requirements of the high/low ends of

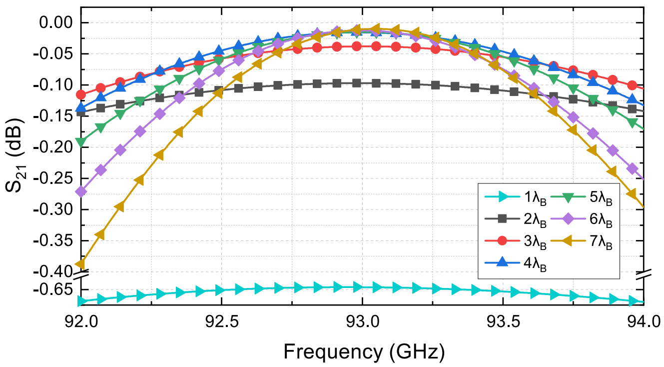


Fig. 4. Mode conversion at a different number of beat wavelengths.

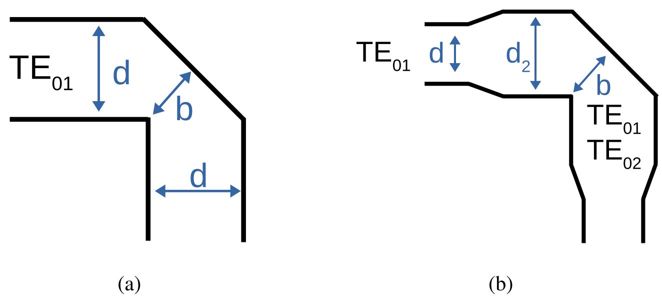


Fig. 5. Miter bends structures. (a) Pure TE_{01} mode. (b) Hybrid TE_{01}, TE_{02} modes.

the bandwidth and the mode purity required at the central frequency.

B. Miter Bend for TE_{01} Mode and Waveguide Taper

The geometry of a 90° miter bend is shown in Fig. 5(a). It consists of two straight waveguides, at a 90° angle to each other with a 45° sloped surface.

The transmission of the operating TE_{01} mode is entirely dependent on the diameter of the waveguide (d) and the distance between its bending point and the sloped surface (b). From the simulations, a small waveguide diameter shows a large reflection, also the miter bend will suffer from diffraction losses, and therefore, the diameter of the waveguide needs to be sufficiently large. A further benefit to the enlarged waveguide is in a reduction of the field strength. Typically, a diameter at least a few times, ~5, the size of the guide wavelength is used. Considering the miter bend with $d = 5\lambda$, the simulations show a transmission of the TE_{01} mode around the −0.4-dB level and reflection better than −30 dB (see Fig. 6).

For a practical system with multiple bends, of a similar design, which provides the flexibility to transport the radiation over a required distance, the diffraction losses can be significant. Further investigation showed that the diffraction losses can be significantly reduced through introducing a mode conversion before the miter bend, for example, to convert from pure TE_{01} into a mixture of higher order TE_{0n} modes, which helps to locate the wave energy more centrally. The conversion can be made by introducing a change of the waveguide diameter. The profile can be determined speedily through optimization techniques, such as particle swarm optimization [24]; however, for simple manufacture, a smoothly tapered waveguide transition [see Fig. 5(b)] was studied.

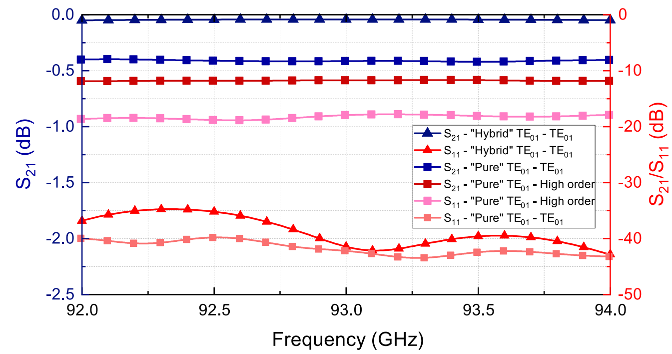


Fig. 6. Transmission parameters of the miter bend.

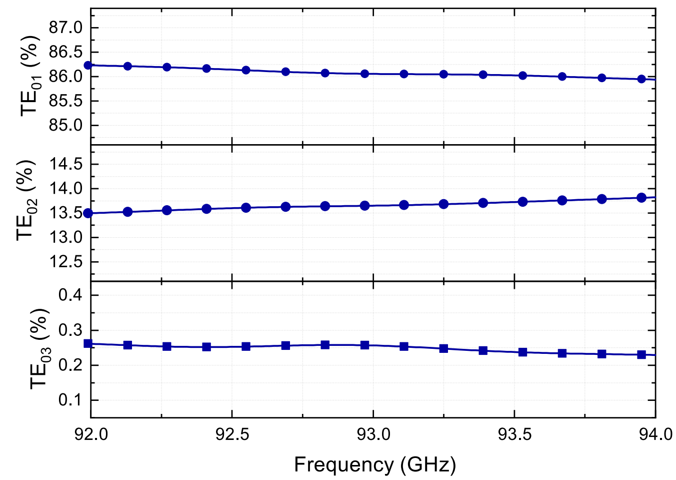


Fig. 7. Simulated mode conversion caused by a linear waveguide taper.

The connection between two waveguides with different diameters can be made through a tapered tube. However, it is important to ensure that any geometry discontinuities are avoided as these would cause unintended mode conversions. The simplest method is to use the smooth linear taper, and the angle of it determines the strength of the conversion to higher order modes TE_{0n}. Simulations showed that the mode conversion to TE_{02} is 4%, 8%, 13.5%, and 20% when the taper angle was 4, 6, 8, and 10, respectively. An angle of 8° was chosen, which resulted in a mode mixture of 86% TE_{01}, 13% TE_{02}, and 0.2% TE_{03} into the miter bend, as shown in Fig. 7. The initial waveguide diameter had a ratio to wavelength which was set as 5.0 and a length of 18.50 mm.

However, the disadvantage for the linear taper is that in the case of a large diameter difference, a long waveguide taper is required. A nonlinear taper, for example, with a sine-square function profile [25], will achieve better performance to maintain the mode content while reducing the taper length by a factor of 2; however, it increases the machining complexity. Therefore, the final design of the waveguide taper will be a balance between its length and machining complexity.

The waveguide taper in the mode converter uses the linear taper. It must be at a specific distance (L_{ph}) from the miter bend in order to properly phase the modes at the point of

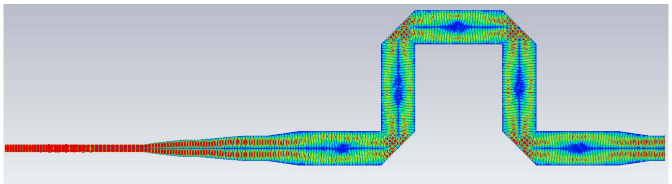


Fig. 8. Simulation model of, and wave propagation through, the *W*-band transmission line system.

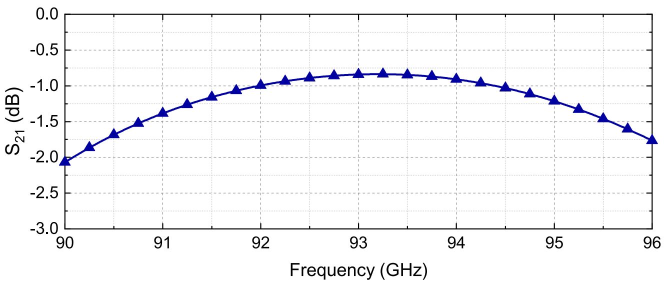


Fig. 9. Simulated *W*-band transmission line system and inset the simulation model.

the bend. A relatively large taper angle of 8.3° could be used to make a suitable amount of mode conversion to TE_{0n} modes. Its accurate length was obtained from a parameter sweep in the numerical simulation. The mode mixture at the central frequency was 86% TE_{01}, 13.5% TE_{02} and 0.25% TE_{03} (see Fig. 7).

In the optimized case, this hybrid miter bend [see Fig. 5(b)] has an input diameter of $d = 5\lambda_0$ and output $d_2 = 6.2\lambda_0$ with taper angle of 8.3° that is set away from the miter bend at $L_{ph} = 16\lambda_0$. Therefore, the hybrid miter bend shows an optimized transmission with an average of −0.04-dB transmission over 92–94 GHz.

III. Simulation Results of *W*-Band Transmission Line System

A *W*-band gyro-TWA was developed at the University of Strathclyde. It achieved an output power of 3.4 kW with the gain of 36–38 dB at a center frequency of 93 GHz [12]. A transmission line system based on the method presented in this article was designed to transport the MMW radiation about 20 m away to the application region. A subsection of this system was investigated with an overall length of 0.4 m with four waveguide bends. The optimized miter bends had an input diameter d of 16.00 mm and a phasing diameter d_2 of 21.40 mm. The taper angle was 8.3°, and the phasing length was 18.50 mm. Each of the waveguides bends, when analyzed individually, has a maximum transmission loss of −0.05 dB with the reflection of under −30 dB.

The simulated geometry (see Fig. 8) comprised of mode converter, taper, and four miter bends separated with smooth guides. To reduce the simulation time, the geometry was simplified; long smooth waveguides were separated into short waveguide sections. The waveguide wall was set with the poor conductivity of 1.0×10^6 S/m, and the effect is to simulate a waveguide length of 0.4 m that is the equivalent of 20 m of oxygen-free high conductivity (OFHC) copper. The overall loss was 0.84 dB at the center frequency (see Fig. 9). This result shows that long lengths of this transmission line are viable for use with a kilowatt level gyro-TWA. It has been shown that the conversion of the TE_{01}-to-TE_{11} mode in the overmoded waveguide can be made with high efficiency [26]. This would allow the addition of a TE_{11} to the HE_{11} mode converter, such as the corrugated [27] waveguide or a smoothly profiled horn [25].

IV. Conclusion and Discussion

In many applications, there is a requirement to transport the MMW signal across long distances. In this article, a transmission line system operating with a TE_{01} mode was studied to meet those needs. The design of the major components, including the mode converter, waveguide taper, and miter bend, was presented. The frequency-independent design process is applicable to different frequencies for different applications. Each component was analyzed as a stand-alone item to achieve an optimal design with consideration of the manufacturing process. The miter bend geometry was analyzed with a pure TE_{01} input and with additional higher order TE_{0n} modes. It was found that the inclusion of those modes resulted in a transmission loss reduction of ten times when compared to the pure TE_{01} design. The guides between miter bends are also very low loss. When considering a conductivity of 5.8×10^7 S/m for the metallic waveguide, the ohmic loss is about 0.006 dB/m at a waveguide diameter of 21.40 mm and a frequency of 93 GHz. To compare to the corrugated waveguide a 110-GHz transmission line was designed for ITER with a calculated loss of 0.002 dB/m at the diameter of 31.75 mm [6]. The full system, with each component and a series of miter bends, showed that the system is able to transport the output from a kilowatt-level MMW source over a very long distance.

At the optimal design, the TE_{11}-to-TE_{01} mode converter achieved a central frequency conversion efficiency of 99.1% while maintaining a better than −35-dB return loss. The miter bend with the higher order mode mixture showed an average of 0.04-dB transmission loss over 92–94 GHz. As an example, a transmission line system that would be situated at the output of a *W*-band gyro-TWA was designed. The circular polarized TE_{11} mode, which is the output mode from the gyro-TWA, was used as the input to the system. With an equivalent overall length of 20 m and four miter bends, the transmission loss was about 0.84 dB, at 93 GHz, when the waveguide was OFHC copper. An extended bandwidth of 90–96 GHz was studied, and the system showed a maximum loss of −2 dB.

References

[1] G. M. Smith *et al.*, "Instrumentation for high sensitivity, high power, millimetre wave, electron paramagnetic resonance," in *Proc. IET Colloq. Millimetre-Wave Terahertz Eng. Technol.*, London, U.K., 2016, pp. 1–5, doi: 10.1049/ic.2016.0017.

[2] F. Leuterer *et al.*, "Experience with the ECRH system of ASDEX-upgrade," *Fusion Eng. Des.*, vol. 53, no. 1, pp. 485–489, 2001, doi: 10.1016/S0920-3796(00)00524-X.

[3] P. J. B. Clarricoats and A. D. Olver, *Corrugated Horns for Microwave Antennas*. London, U.K.: Peregrinus, 1984, doi: 10.1049/PBEW018E.

[4] E. J. Kowalski *et al.*, "Linearly polarized modes of a corrugated metallic waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 11, pp. 2772–2780, Nov. 2010, doi: 10.1109/TMTT.2010.2078972.

[5] L. Zhang, W. He, J. Clarke, K. Ronald, A. D. R. Phelps, and A. Cross, "Systematic study of a corrugated waveguide as a microwave undulator," *J. Synchrotron Radiat.*, vol. 26, no. 1, pp. 11–17, Jan. 2019, doi: 10.1107/S1600577518014297.

[6] J. L. Doane, "Design of circular corrugated waveguides to transmit millimeter waves at ITER," *Fusion Sci. Technol.*, vol. 53, no. 1, pp. 159–173, Jan. 2008, doi: 10.13182/fst08-a1662.

[7] P. P. Woskov, V. S. Bajaj, M. K. Hornstein, R. J. Temkin, and R. G. Griffin, "Corrugated waveguide and directional coupler for CW 250-GHz gyrotron DNP experiments," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 6, pp. 1863–1869, Jun. 2005, doi: 10.1109/TMTT.2005.848097.

[8] A. A. Bogdashov and G. G. Denisov, "Asymptotic theory of high-efficiency converters of higher-order waveguide modes into eigenwaves of open mirror lines," *Radiophys. Quantum Electron.*, vol. 47, no. 4, pp. 283–296, Apr. 2004, doi: 10.1023/B:RAQE.0000047649.17664.6e.

[9] V. I. Belousov, A. A. Bogdashov, A. V. Chirkov, G. G. Denisov, and S. V. Kuzikov, "New components for TE_{01} transmission lines," in *Proc. Int. Workshop Strong Microw. Plasmas*, Nizhny Novgorod, Russia, vol. 2, 2000, pp. 943–948.

[10] A. A. Bogdashov *et al.*, "High-power Ka-band transmission line with a frequency bandwidth of 1 GHz," *Radiophys. Quantum Electron.*, vol. 58, no. 10, pp. 777–788, Mar. 2016, doi: 10.1007/s11141-016-9650-5.

[11] A. Bogdashov, G. Denisov, D. Lukovnikov, Y. Rodin, and J. Hirshfield, "Ka-band resonant ring for testing components for a high-gradient linear accelerator," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 10, pp. 3152–3155, Oct. 2005, doi: 10.1109/TMTT.2005.855357.

[12] W. He, C. R. Donaldson, L. Zhang, K. Ronald, A. D. R. Phelps, and A. W. Cross, "Broadband amplification of low-terahertz signals using axis-encircling electrons in a helically corrugated interaction region," *Phys. Rev. Lett*, vol. 119, no. 18, 2017, Art. no. 184801, doi: 10.1103/PhysRevLett.119.184801.

[13] L. Zhang, C. R. Donaldson, P. Cain, A. W. Cross, and W. He, "Amplification of frequency-swept signals in a W-band gyrotron travelling wave amplifier," *IEEE Electron Device Lett.*, vol. 39, no. 7, pp. 1077–1080, Jul. 2018, doi: 10.1109/LED.2018.2836868.

[14] G. Liu *et al.*, "A millimeter wave high-order TE_{13} mode converter," *IEEE Trans. Electron Devices*, vol. 63, no. 7, pp. 2907–2911, Jul. 2016, doi: 10.1109/TED.2016.2562025.

[15] D. A. Constable, X. S. Fampris, K. Ronald, W. He, C. G. Whyte, and C. W. Robertson, "A novel cylindrical $TE_{2,1}$ mode converter," *Rev. Sci. Instrum.*, vol. 81, no. 9, Sep. 2010, Art. no. 094702, doi: 10.1063/1.3480994.

[16] Y. Wang *et al.*, "Wideband circular TE_{21} and TE_{01} mode converters with same exciting topologies," *IEEE Trans. Electron Devices*, vol. 63, no. 10, pp. 4088–4095, Oct. 2016, doi: 10.1109/TED.2016.2596785.

[17] C. Schulz, C. Baer, T. Musch, I. Rolfes, and B. Will, "Investigation of a circular TE_{11}-TE_{01}-mode converter in stepped waveguide technique," *Int. J. Microw. Wireless Technol.*, vol. 7, nos. 3–4, pp. 229–237, Jun. 2015, doi: 10.1017/S1759078715000203.

[18] G. G. Denisov, G. I. Kalynova, and D. I. Sobolev, "Method for synthesis of waveguide mode converters," *Radiophys. Quantum Electron.*, vol. 47, no. 8, pp. 615–620, Aug. 2004, doi: 10.1023/B:RAQE.0000049559.74097.86.

[19] M. Thumm, "High-power millimetre-wave mode converters in overmoded circular waveguides using periodic wall perturbations," *Int. J. Electron.*, vol. 57, no. 6, pp. 1225–1246, Dec. 1984, doi: 10.1080/00207218408938998.

[20] L. Zhang, W. He, J. Clarke, K. Ronald, A. D. R. Phelps, and A. W. Cross, "Microwave undulator using a helically corrugated waveguide," *IEEE Trans. Electron Devices*, vol. 65, no. 12, pp. 5499–5504, Dec. 2018, doi: 10.1109/TED.2018.2873726.

[21] L. Zhang *et al.*, "Multi-mode coupling wave theory for helically corrugated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 1, pp. 1–7, Jan. 2012, doi: 10.1109/TMTT.2011.2170848.

[22] G. G. Denisov, V. L. Bratman, A. D. R. Phelps, and S. V. Samsonov, "Gyro-TWT with a helical operating waveguide: New possibilities to enhance efficiency and frequency bandwidth," *IEEE Trans. Plasma Sci.*, vol. 26, no. 3, pp. 508–518, Jun. 1998, doi: 10.1109/27.700785.

[23] D. B. McDermott, J. Pretterebner, C. K. Chong, C. F. Kinney, M. M. Razeghi, and N. C. Luhmann, "Broadband linearly polarized beat-wave TE_{m1}/TE_{11} mode converters," *IEEE Trans. Microw. Theory Techn.*, vol. 44, no. 2, pp. 311–317, Feb. 1996, doi: 10.1109/22.481581.

[24] A. A. Bogdashov and Y. V. Rodin, "Mode converter synthesis by the particle swarm optimization," *Int. J. Infr. Millim. Waves*, vol. 28, no. 8, pp. 627–638, Jun. 2007, doi: 10.1007/s10762-007-9248-2.

[25] L. Zhang *et al.*, "Optimization and measurement of a smoothly profiled horn for a W-band gyro-TWA," *IEEE Trans. Electron Devices*, vol. 64, no. 6, pp. 2665–2669, Jun. 2017, doi: 10.1109/TED.2017.2687949.

[26] A. Patel *et al.*, "Millimeter-wave TE_{01}–TE_{11}–HE_{11} mode converter using overmoded circular waveguide," *J. Electromagn. Waves Appl.*, vol. 32, no. 14, pp. 1768–1778, Sep. 2018, doi: 10.1080/09205071.2018.1468286.

[27] P. McElhinney *et al.*, "An output coupler for a W-band high power wideband gyroamplifier," *IEEE Trans. Electron Devices*, vol. 64, no. 4, pp. 1763–1766, Apr. 2017, doi: 10.1109/TED.2017.2660304.