URSI - RCRS 2022, IIT (Indore), India, 1 - 4 December, 2022

Higher Order Mode Generation for Gyrotron Using Fundamental Mode

Maniul Haque [1] and Khan Masood Parvez [2]
(1) Newcastle University, Newcastle upon Tyne NE1 7RU, England
(2) Aliah University, Kolkata, India 700160

Abstract

The contribution of this paper is to propose a higher order mode generation for gyrotron using fundamental mode. The proposed structure aerates two higher order modes – $TE_{6,2}$ and TE 10,1 because their first kind of Bessel function values is almost equal. The $TE_{6,2}$ mode is very useful for gyrotron amplification, whereas $TE_{10,1}$ is an undesired higher-order mode. We suppressed the $TE_{10,1}$ mode by properly loading high conductive wire.

1. Introduction

A higher-order mode generator is essential for specific applications, such as performance tests of a Gaussian mode converter in a powerful microwave source, feeding circuits for gyrotron amplifiers etc. It is one of the challenging tasks for the research community due to its frequency residing in the millimeter-wave regime and operating mode being highly over-mode. A gyrotron is a vacuum electronics tube device to generate high power and high-frequency radiation. It is used in different industrial application for heating purposes. For instance, research experiments in nuclear fusion to heat plasmas and manufacturing industries, as a rapid heating tool in processing glass and composites, as well as for solar system and semiconductor industry. Gyrotron is also very popular in military applications.

The basic idea and its application on powerful source gyrotron has been described in [1]. High-power microwave sources and its technologies are shown in [2]. Gyrotron for various applications has been noted in [3]-[11]. Quasi-optical mode converter has been illustrated in [12] for transforming $TE_{22,6}$ mode at 110GHz gyrotron. A quasi-optical approach for higher-order mode generation has been suggested and tested in [13]-[14]. Theoretical discussion on non-linear trappers for high power gyrotron is noted in allusion [15]. Waveguide mode generator with corrugate configuration to generate the desired mode is explained in [16]-[18]. Higher-order mode generator by direct launched the fundamental mode is shown in [19]. The list of the first 700 zeros of the Bessel function is presented in [20]. The basic concept of microwave circuits and devices is noted in [21].

In this paper, we proposed a higher order mode generation for gyrotron at 95 GHz using the fundamental

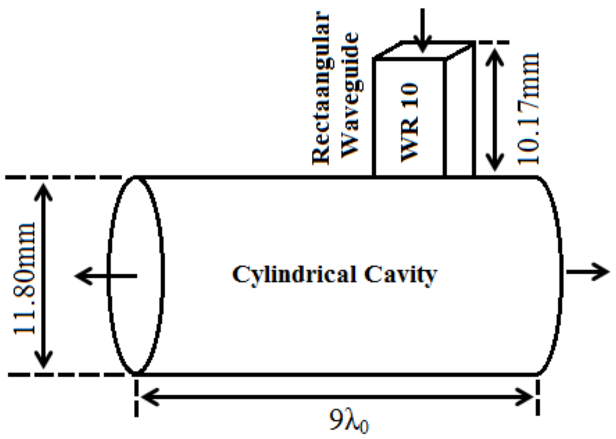

Figure 1. Cylindrical cavity magnetically coupled with rectangular waveguide

mode of rectangular waveguide (WR10) at 59 GHz. The fundamental mode is magnetically coupled with a cylindrical cavity. As a result, the cylindrical cavity generates the desired $TE_{6,2}$ mode with reasonable reflection coefficient and transmission coefficient. When we attempt to increase the bandwidth of $TE_{6,2}$ mode, we discover $TE_{10,1}$ mode is also present at that 95GHz frequency since the zero Bessel function values between desired mode and undesired mode ($TE_{10,1}$) are quite close to each other. Therefore, our next objective is to suppress the undesired mode and improve the desired mode performance for the gyrotron In this case, we introduced twenty highly conductive metallic wires inside the cylindrical cavity at its unwanted mode position, maintaining equal angle of separation between all the installed highly conductive wires. Additionally, we were able to suppress the undesired mode in order to increase the transmission coefficient and bandwidth of TE_{62} mode.

.

2. Higher Order Mode Generator

A cylindrical cavity is designed for higher-order mode generation as presented in Figure 1. The $TE_{6,2}$ mode can be generated at 95 GHz using a cylindrical cavity. Equation (1) and (2) are used to calculate the cut-off frequency of the cavity [21].

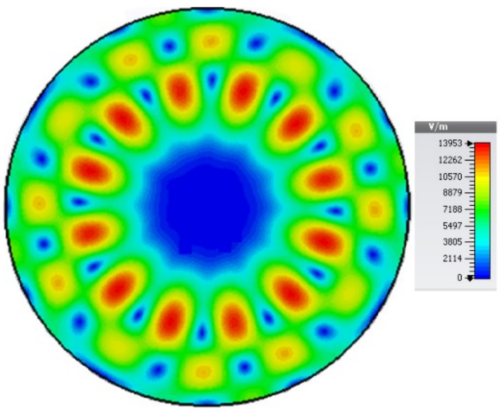

Figure 2. TE$_{6,2}$ mode, generate by cylindrical cavity with rectangular waveguide at 95GHz

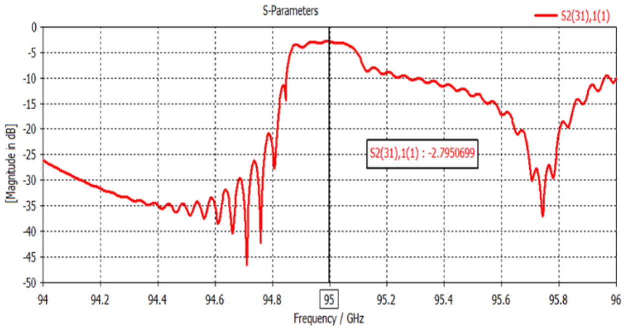

Figure 3. Transmission coefficient of TE$_{6,2}$ mode

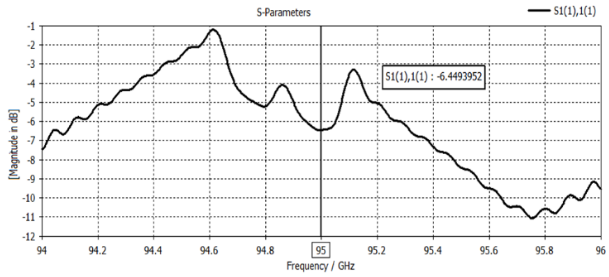

Figure 4. Reflection coefficient realized by rectangular wave guide.

$$K_c = \frac{X'_{np}}{a} \quad \ldots\ldots\ldots\ldots \text{(1)}$$

$$f_c = \frac{C\,K_C}{2\pi} \ldots\ldots\ldots\ldots \text{(2)}$$

Where C is the velocity of light, f_c is the cut-off frequency, K_C represents the cut-off wave number, a is the radius of the cylindrical cavity and X'_{np} denotes the pth zeros of nth odder first kind Bessel function. The diameter of the cylindrical cavity is 11.80 mm and its length is 9λ_0, where λ_0 represents the wavelength of that cut-off frequency. It is fed by the fundamental mode of rectangular waveguide (WR10) at 59 GHz. The fundamental mode is magnetically coupled with a cylindrical cavity. The length of the rectangular waveguide is 10.17 mm.

As a result, the cylindrical cavity generates the higher order TE$_{6,2}$ mode at 95 GHz. It is well observed in Figure 2. From the Figure 3, the optimum power transmission of

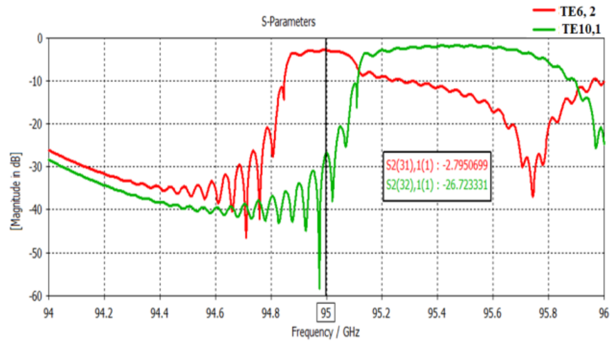

Figure 5. Transmission coefficient of TE$_{6,2}$ and TE$_{10,1}$

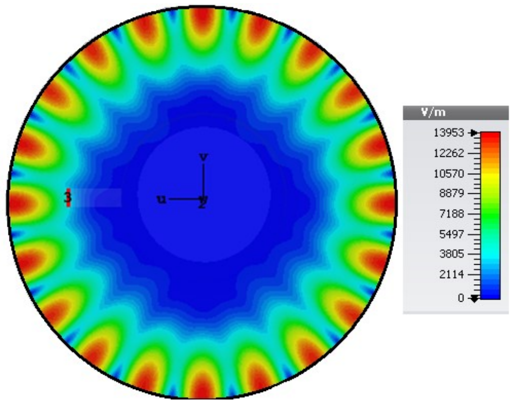

Figure 6. TE$_{10,1}$ mode, generate by cylindrical cavity with rectangular waveguide at near 95GHz

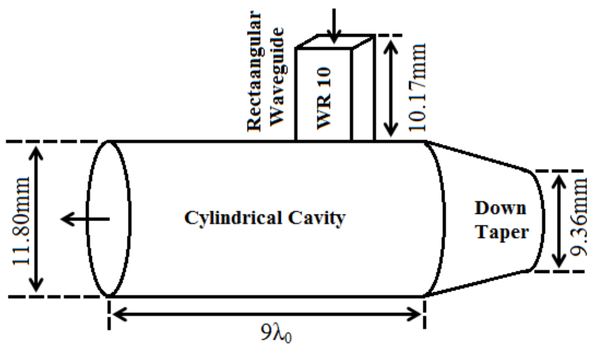

Figure 7. proposed cavity with down trapper

the corresponding mode through the cylindrical cavity, is -2.79 dB. Power transmission in that TE$_{6,2}$ mode is 0 dB in the ideal case. According to Figure 4, the rectangular cavity produces the reflection coefficient of the TE$_{6,2}$ mode. We are now working to increase the desired mode's bandwidth. Then, we discovered that TE$_{10,1}$ mode is also present there, interrupting the desired response. However, the TE$_{10,1}$ mode is produced a good transmission coefficient and bandwidth. The transmission coefficient of both TE$_{6,2}$ and TE$_{10,1}$ modes are illustrated in Figure 5. This TE$_{10,1}$ mode is unwanted in this scenario. The TE$_{10,1}$ mode at the cylindrical cavity is presented in Figure 6. The main reason behind these two modes appearance in very close frequency intervals is because of the first kind of Bessel function. The magnitude of the first kind of Bessel function

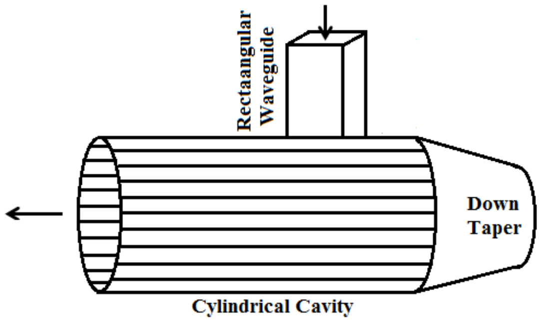

Figure 8. Proposed cylindrical cavity with properly loaded conductive wires.

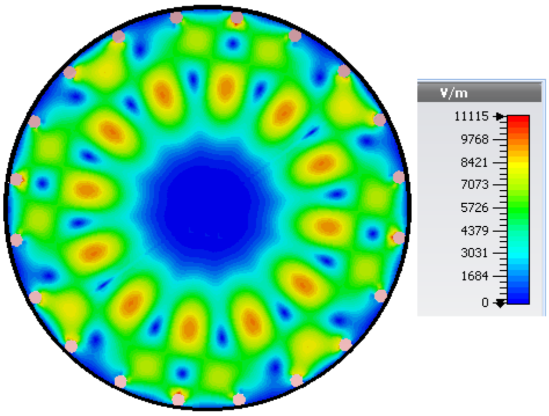

Figure 9. $TE_{6,2}$ mode of Figure 8.

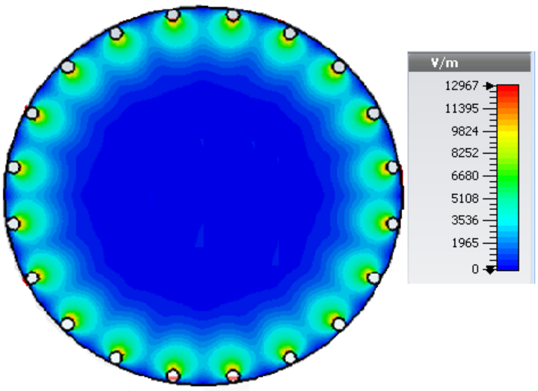

Figure 10. $TE_{10,1}$ mode of Figure 8

for $TE_{6,2}$ mode is 11.73, and the value for $TE_{10,1}$ mode is 11.77 [20]. We need to suppress the $TE_{10,1}$ mode from our cylindrical cavity to obtain a higher bandwidth of $TE_{6,2}$ mode.

We used a down trapper to control the energy flow in a particular one direction. The proposed scheme is depicted in Figure 7. The diameter of the down trapper is less than the diameter of the cylindrical cavity. If we put the radius value of the down trapper cavity in equation number 2, we get a higher cut-off frequency for down trapper compare to our desired frequency. For this reason, the mode generated inside the cylindrical cavity will not flow through the down trapper. Thus, we obtain the one-direction power flow needed for the gyrotron.

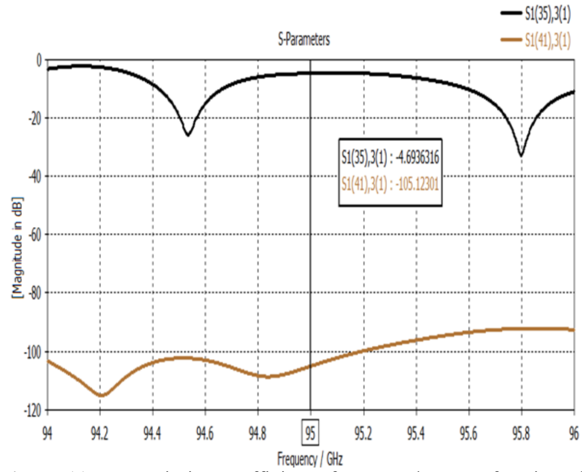

Figure 11. Transmission coefficient of $TE_{6,2}$ and $TE_{10,1}$ after introduced the conductive wire

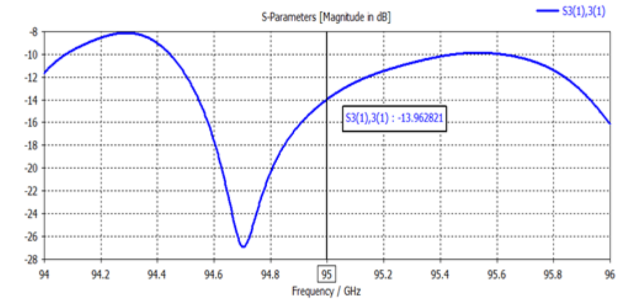

Figure 12. Reflection coefficient realized by rectangular wave after introduced the conductive wire

3. Unwanted Higher Order Mode Suppression

To improve the transmission coefficient and the bandwidth of desired $TE_{6,2}$ mode, we introduced conductive wires inside the cylindrical cavity to degrade the power transmission of the unwanted $TE_{10,1}$ mode. The cylindrical cavity with properly loaded conductive wires is presented in Figure 8. Here we installed twenty conductive wires to suppress the $TE_{10,1}$ mode maintaining equal angle separation between two conductive wires. Thus we got a better response in $TE_{6,2}$ mode. The $TE_{6,2}$ mode is shown in Figure 9. The $TE_{10,1}$ mode is totally suppressed from the cylindrical cavity shown in Figure 10. After suppressing the $TE_{10,1}$ mode, we achieved a wider bandwidth than the previous response.

The transmission coefficient of $TE_{6,2}$ and $TE_{10,1}$ mode is shown in Figure 11. It clearly observed from this transmission coefficient versus frequency plot that the $TE_{10,1}$ mode is suppressed after the introduction of conductive wires. In Figure 12, the reflection coefficient response is better than the previous approach.

4. Conclusions

In this paper, we proposed a higher order mode generation for gyrotron using fundamental mode. The proposed structure aerates two higher-order modes $-TE_{6,2}$ and $TE_{10,1}$ because of their first kind of Bessel function values. The $TE_{6,2}$ mode is very useful for gyrotron amplification, whereas $TE_{10,1}$ is an unwanted higher-order mode. We make an approach to suppress the $TE_{10,1}$ mode by properly loading conductive wires.

5. Acknowledgements

The authors would like to thankful CSIR CEERI Pilani for their help.

6. References

1. M.v.Kartikeyan, E.Borie and M.K.A. Thum, "Gyrotrons: high power microwave and millimeter wave technology" *Springer-Verlag Berlin Heidelberg* 2004, doi: 10.1007/978-3-662-07637-8.
2. R.J.Barker,"Highpower microwave sources and technologies", *IEEE –wiely press*. June200.
3. M. Thumm, "High power gyro-devices for plasma heating and other applications,"*J. Infrared,Millim., Terahertz Waves*, **26**, 4, April. 2005.pp. 483–503, doi: 10.1007/s10762-005-4068-8.
4. S. H. Gold and G. S. Nusinovich, "Review of high-power microwave source research," *Rev. Sci. Instrum.*, **68**, 11, November. 1997, pp. 3945–3974, doi:10.1063/1.1148382.
5. D. Bora, "SST and ADITYA tokomak research in India," *Braz. J. Phys.*, **32**, 1, March 2002, pp. 193–216. doi: 10.1590/S0103-97332002000100032.
6. H. Khatun, R. R. Rao, A. K. Sinha, and S. N. Joshi, "Optimization of magnetic field for maximum output power of a 42 GHz CW/Long pulse gyrotron," in *Proc. IEEE-IVEC*, Rome, Italy, April 2009, pp. 98–99, doi:10.1109/IVELEC.2009.5193366.
7. H. Khatun, U. Singh, N. Kumar, A. Bera, R. R. Rao, and A. K. Sinha, "Design of interaction cavity for 42 GHz, 200 kW CW/Long pulse gyrotron," in *Proc. IEEE-IVEC*, Rome, Italy, April 2009, pp. 94–95, doi:10.1109/IVELEC.2009.5193364.
8. V. Yadav, S. Sharan, H. Khatun, N. Kumar, M. K. Alaria, B. Jha,S. C. Deorani, A. K. Sinha, and P. K. Jain, "Cold characterization of cylindrical open resonator for gyrotron," *Infrared Phys. Technol.*, **54**, 4, July 2011, pp. 337–342, doi: 10.1016/j.infrared.2011.02.003.
9. A. Kumar, H. Khatun, N. Kumar, U. Singh, V. Vyas, and A. K. Sinha, "Particle-in-cell analysis of beam–wave interaction in gyrotron cavity with tapered magnetic field," *Can. J. Phys.*, **88**, 11, November 2010, pp. 857–861, doi:10.1139/P10-078.
10. M. V. Kartikeyan, A. Kumar, S. Kamakshi, P. K. Jain, S. Illy, E. Borie, B. Piosczyk, and M. K. Thumm, "RF behavior of a 200-kW CW gyrotron," *IEEE Trans. Plasma Sci.*, **36**, 3, June 2008, pp. 631–636, doi: 10.1109/TPS.2008.923762.
11. M. Blank, K. Kreischer, and R. J. Temkin, "Theoretical and experimental investigation of a quasi-optical mode converter for a 110-GHz gyrotron," *IEEE Trans. Plasma Sci.*, **24**, June 1996, pp. 1058–1066, doi: 10.1109/27.533113.
12. N.L. Alexandrov, G.G. Denisov, D.R. Whaley, and M.Q. Tran, "Low power excitation of gyrotron-type modes in a cylindrical waveguide using quasi-optical techniques", *Int J Electron,* **79**, 1995, pp.215–226, doi: 10.1080/00207219508926263.
13. M. Pereyaslavets, O. Braz, S. Kern, M. Losert, A. Mobius, and M. Thumm, "Improvements of mode converters for low-power excitation of gyrotron-type modes", *Int J Electron*, **82**, 1997, pp. 107–115, doi:10.1080/002072197136291
14. W. Lawson, "Theoretical evaluation of nonlinear tapers for a highpower gyrotron," IEEE *Trans. Microwave Theory Tech.,* **38**, November 1990, pp. 16 17-1622, doi:10.1109/22.60007.
15. W. Lawson, M.R. Arjona, B.P. Hogan, and R.L. Ives, "The design of serpentine-mode converters for high-power microwave applications", *IEEE Trans Microwave Theory Tech* , **48**, May 2000, pp. 809-814, doi:10.1109/22.841875.
16. Y. Kiwamoto, T. Honda, A. Kasugai, T. Saito, S. Miyoshi, O. Wada, and M. Nakajima, "Analysis and optimization of stepwise modulated TE0n mode converter", *Rev Sci Instrum*, **62**,1991,pp. 178– 188.
17. Q. Zhang, C.W. Yuan, and L. Liu, "Theoretical design and analysis for TE_{20}-TE_{10} rectangular waveguide mode converters", *IEEE Trans Microwave Theory Tech*, **60**, April 2012, pp. 1018–1026, doi: 10.1109/TMTT.2011.2182206.
18. M.Seok, E.Choi, "Higher order mode generation in millimeter wave gegim by directly lunched fundamental mode", *Wiely Microwave and Optical Technology Letters*, **56**, 7, Jully 2014, pp-1648-1651, doi: 10.1002/mop.28408.
19. C.L.Beattile, "Table of First 700 Zeros of Bessel Functions-J_l (x) and $J'^{l}(x)$", The Bell lab system Journal, **37**, May1958, pp.-689-697, doi: 10.1002/j.1538-7305.1958.tb03881.x.
20. S.Y.Liao,"Microwave devices and cuircuits", 3rd Edition, *Pearson*,2013
21. CST Microwave stidio, 2013.