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Single Mode Cold Cavity Solver Code for Gyrotron Resonator

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Abstract—**This paper, presents the development of single mode cold cavity solver (SMCCS) code. SMCCS code computes the frequency, *Q*-factor and axial field profile of eigenmodes in a gyrotron resonator. SMCCS has been developed using the cyclic coordinate search method along with golden section search. The novel optimization approach reduces computational complexity as it does not require computation of gradients of the radiation boundary condition. SMCCS has been used to compute the first-order as well as high-order axial modes in gyrotron resonators operating at 10-GHz, 170-GHz and 1-THz. The results obtained are in good quantitative agreement with the experimental and numerical data available in the published literature.**

Keywords— ***Broadband continuous frequency tuning, golden section search, gyrotron, high-order axial modes (HOAM), open resonator, optimization, sub-terahertz, terahertz.***

I. INTRODUCTION

Gyrotron has produced most powerful continuous wave coherent radiation at millimeter [1] and sub-millimeter wavelengths [2], leading to diverse applications like fusion plasma heating [1] and food inspection [3]. Interaction between electron beam and electromagnetic field takes place in the open resonator of the gyrotron oscillator. The propagation characteristics of waves in a typical gyrotron resonator (Fig. 1) is based on the theory of weakly irregular waveguides which involves solution of second order differential equation for the RF field profile subject to radiation boundary conditions [4]. Many computer codes have been developed by different research groups worldwide following the approach described in [4]. These codes have been used extensively for the design and analysis of gyrotron resonators [5],[6]. Most of these codes use steepest descent based optimization algorithm which is computationally complex as it requires computation of gradients of radiation boundary conditions [7]. To solve this problem, a novel optimization approach has been used which has led to the development of single mode cold cavity solver (SMCCS) code [8]. The novel approach obviates the computation of gradients of radiation boundary condition and hence reduces computational complexity.

In this paper, we elucidate the novel optimization approach used for the development of SMCCS code and present the computation of first-order axial modes (FOAMs) for resonators operating at 10-GHz and 170-GHz. The results have been compared with the experimental (10-GHz) and the numerical data (170-GHz) available in the published literature [9]–[11]. High-order axial modes (HOAMs), computed for resonator operating at 1-THz, have also been presented.

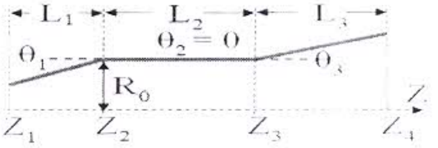

Fig. 1. Typical gyrotron resonator configuration

II. APPROACH

The numerical approach involves solution of $\left[d^2/dz^2 + k_{z,s}^2(z)\right]V_s(z) = 0$, where $k_{z,s}^2(z) = (\omega/c)^2 - k_{\perp,s}^2$and $\omega = \omega_r(1 + i/2Q_D)$, in such a way that the two unknown quantities, the real part of the RF frequency ω_r, and the diffractive quality factor Q_D, are varied until the radiation boundary condition $\left[dV_s/dz + ik_{z,s}V_s\right] = 0$ is satisfied at $z = Z_4$. The unknown quantities, ω_r and Q_D, are found by an iterative optimization procedure which consists of cyclic coordinate search along with golden section search. In the cyclic coordinate search method, one variable is changed at a time while the other variables are kept constant. This leads to the reduction of the challenging 2-D optimization problem into a sequence of two different 1-D searches i.e. one along Q_D and another along f_r direction. The search along each design variable is carried out using golden section search which is a popular and robust line search method. For detailed numerical implementation see [8] and references therein.

III. RESULTS AND DISCUSSION

This section presents the computation of eigenmodes in three resonators with increasing resonant frequency, f_r.

A. Gyrotron Resonator With $f_r = 10$ GHz

A resonator designed and characterized [9] to operate at 10-GHz with following geometrical features: θ_1=0.8°, θ_2=0°, θ_3=3°, L_1=105 mm, L_2=157.5 mm, L_3=157.5 mm, and R_0=33.65 mm, has been considered as the first example. Experimentally measured [9] values of resonant frequencies and loaded Q-factor, Q_L for $\mathrm{TE}_{2,2,1}$, $\mathrm{TE}_{3,2,1}$, and $\mathrm{TE}_{5,1,1}$ modes have been compared with the numerical results of SMCCS code in Table 1. The electrical conductivity of copper has been taken as 4.3×10^7 S/m in [9].

TABLE I
COMPARISON BETWEEN COMPUTED AND MEASURED [9] VALUES OF f_r AND Q_L IN A 10-GHZ RESONATOR.

	Computed using SMCCS		Measured [9]	
Mode	f_r (GHz)	Q_L	$f_r \pm 7\times10^{-4}$ (GHz)	Q_L
$\mathrm{TE}_{2,2,1}$	9.5401	853	9.5206	859 ± 23
$\mathrm{TE}_{3,2,1}$	11.3950	1285	11.3697	1223 ± 26
$\mathrm{TE}_{5,1,1}$	9.1286	785	9.1035	752 ± 19

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It can be seen from Table I that the resonant frequency varies by a maximum of 0.27 % while the maximum change in Q_L value is 4.82 %. The remarkable agreement between the computed and the measured results proves the efficacy of the approach used for the development of SMCCS code.

B. Gyrotron Resonator With f_r = 170 GHz

In this example, a resonator designed [10] to operate at 170-GHz in $\mathrm{TE}_{10,4,1}$ mode has been considered. The geometrical parameters are as follows: θ_1=2.54°, θ_2=0°, θ_3=2.98°, L_1=8.8 mm, L_2=12 mm, L_3=14 mm, and R_0=6.7 mm. Fig. 2 (a)–(b) shows the comparison of resonant frequency and Q_L value as a function of cavity midsection length, L_2, (keeping other parameters fixed) as computed by SMCCS code and reported in [10]. Finite-integration-based formulation has been used in [10] for numerical analysis. It should be noted that accurate theoretical model [4] used in SMCCS code has led to an increase in the Q_L value. Maximum increase observed in the Q_L value is 34.04%. On the other hand, the resonant frequency varies by a maximum of 0.16%.

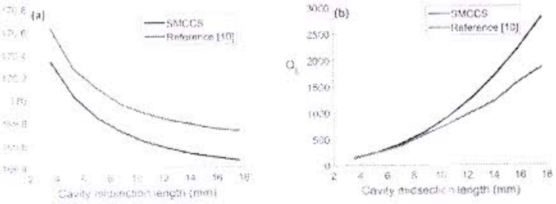

Fig. 2. Cavity midsection length Vs (a) Frequency, and (b) Quality factor corresponding to 170-GHz resonator operating in $\mathrm{TE}_{10,4,1}$ mode.

C. Gyrotron Resonator With f_r = 1 THz

Finally, a very-high-Q resonator designed [11] to operate at 1-THz in $\mathrm{TE}_{9,7}$ mode has been considered. Resonator geometry is as follows: θ_1=4°, θ_2=0°, θ_3=2°, L_1=5 mm, L_2=12 mm, L_3=10 mm, and R_0=1.5 mm. Fig. 3(a)–(d) represents the resonant frequency, Q_D value and axial field profile of $\mathrm{TE}_{9,7,1} - \mathrm{TE}_{9,7,4}$ modes. It can be seen that the f_r value increases from 1034.74 GHz when q=1 to 1035.76 GHz when q=4. On the other hand, the Q_D value undergoes sharp reduction as the axial index, q, increases, which is characteristic of a typical gyrotron resonator [4]. It is worth mentioning that broadband continuous frequency tuning can be achieved in a gyrotron resonator by excitation of successive HOAMs [12].

IV. CONCLUSION

In this paper, development of SMCCS code has been presented. Cyclic coordinate search method (along with golden section search) used for the optimization of resonant frequency and Q-factor reduces computational complexity as it does not require any gradient information. SMCCS code has been used for the cold cavity analysis of gyrotron resonators operating over wide frequency range varying from 10 GHz to 1-THz. Numerical results of SMCCS code have been found to be in good quantitative agreement with the experimental and numerical results available in the published literature which validates the efficacy of the approach used for the development of the code.

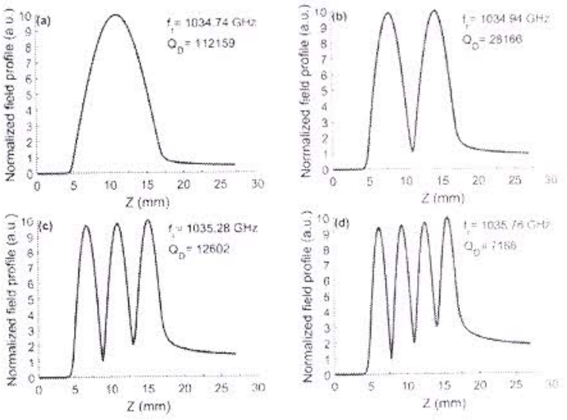

Fig. 3. Normalized field profiles for the first four axial $\mathrm{TE}_{9,7,q}$ modes (q = 1, 2, 3, and 4) corresponding to 1-THz resonator.

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REFERENCES

[1] M. Thumm, "State-of-the-Art of High Power Gyro-Devices and Free Electron Masers (Update 2017)," IHM, Karlsruhe Institute of Technology, Karlsruhe, Germany, KIT Scientific Reports 7750, 2018.

[2] N. Kumar, U. Singh, A. Bera, and A. K. Sinha, "A review on the sub-THz/THz gyrotrons," *Infrared Phys Technol*, vol. 76, pp. 38-51, 2016/05/01/ 2016, DOI: https://doi.org/10.1016/j.infrared.2016.01.015.

[3] S. T. Han, W. K. Park, and H. S. Chun, "Development of Sub-THz gyrotron for real-time food inspection," in *2011 International Conference on Infrared, Millimeter, and Terahertz Waves*, 2011, pp. 1-2.

[4] S. N. Vlasov, G. M. Zhislin, I. M. Orlova, M. I. Petelin, and G. G. Rogacheva, "Irregular waveguides as open resonators," *Radiophysics and Quantum Electronics*, vol. 12, pp. 972-978, August 01 1969, DOI: 10.1007/bf01031202.

[5] A. W. Fliflet and M. E. Read, "Use of weakly irregular waveguide theory to calculate eigenfrequencies, Q values, and RF field functions for gyrotron oscillators," *Int J Electronics*, vol. 51, pp. 475-484, Oct 1981, DOI: 10.1080/00207218108901350.

[6] E. Borie and O. Dumbrajs, "Calculation of eigenmodes of tapered gyrotron resonators," *Int J Electronics*, vol. 60, pp. 143-154, Feb 1986, DOI: 10.1080/00207218608920768.

[7] O. Dumbrajs, T. Idehara, T. Saito, and Y. Tatematsu, "Calculations of Starting Currents and Frequencies in Frequency-Tunable Gyrotrons," *Japanese Journal of Applied Physics*, vol. 51, pp. 126601, 2012, DOI: 10.1143/JJAP.51.126601.

[8] Vishant, A. Bera, A. K. Sinha, and Chandrashekhar, "A Novel Approach for Computation of High-Order Axial Modes in a Gyrotron Resonator," *IEEE Transactions on Electron Devices*, vol. 65, pp. 5505-5510, 2018, DOI: 10.1109/TED.2018.2877843.

[9] P. J. Castro, J. J. Barroso, R. A. Correa, and M. C. A. Nono, "Cold tests of A 10-GHz gyrotron cavity," *Int J Infrared Milli Waves*, vol. 13, pp. 91-104, Jan. 1992, DOI: 10.1007/bf01011210.

[10] A. Bera, "Conceptual Design Report for 170 GHz, 100 kW Gyrotron Pre-Prototype," MWD, CSIR-Central Electronics Engineering Research Institute, Pilani, India, 2018.

[11] M. Glyavin, N. Ginzburg, A. Luchinin, V. Manuilov, M. Morozkin, G. Nusinovich, *et al.*, "Numerical analysis of THz gyrotrons operation conditions for efficient generation at cyclotron harmonics," University of Fukui, Bunkyo, Fukui, Japan FIR FU-121, 2013.

[12] M. K. Hornstein, V. S. Bajaj, R. G. Griffin, K. E. Kreischer, I. Mastovsky, M. A. Shapiro, *et al.*, "Second harmonic operation at 460 GHz and broadband continuous frequency tuning of a gyrotron oscillator," *IEEE Trans Electron Devices*, vol. 52, pp. 798-807, May 2005, DOI: 10.1109/TED.2005.845818.