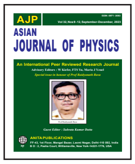

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Design of a 94 GHz PBG-based multi-beam EIK

Vemula Bhanu Naidu[a], Dipanjan Gope[b] and Subrata Kumar Datta[a]
[a]*Microwave Tube Research and Development Centre (MTRDC), DRDO, Bengaluru-560 013, India*
[b]*Department of Electrical Communication Engineering, Indian Institute of Science (IISc), Bengaluru-560 012, India*

Dedicated to Prof B N Basu

Feasibility of a photonic band-gap (PBG) based multiple-beam extended interaction klystron amplifier was explored analytically through 3D electromagnetic simulation. The design of the RF interaction structure was carried out employing a six-defect PBG-based cavity structure operating at around 94 GHz for facilitating electron-wave interaction at 2π-mode with 6 electron beams each carrying 300 mA current at the accelerating potential of 17.5 kV. The device is configured using an input cavity, four buncher cavities and an output cavity and the design was optimized through simulation using commercial electromagnetic simulation code CST Studio. Particle-in-cell simulation promises peak output power of about 3.7 kW with gain of about 55 dB, hot 3 dB bandwidth of about 0.17% and electronic efficiency of about 11.7%.
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Keywords: Extended interaction klystron, Multiple-beam klystron, Photonic band-gap (PBG) cavity structure.

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1 Introduction

Extended interaction klystrons (EIKs) remained the popular choice as high-power microwave sources at mm-wave frequencies [1]. However, a major challenge in high frequency EIKs has been the realization of smaller transverse dimensions as the frequency increases [2]. Photonic band-gap (PBG) based interaction structures provided a solution towards this limitation. Increasing the transverse dimensions of the interaction structure of an EIK was explored by employing a metal-rod-lattice type single-defect PBG structure [3-4] that supported RF interaction with a single circular electron beam. Recently, the authors proposed a novel concept of a multiple-beam EIK using multiple-defect PBG-based interaction structure in which the electron beams are supported through the defect tunnels in the structure [5]. Based on the initial studies carried out by the authors, this paper proposes a design of a multi-defect PBG-based multiple-beam extended interaction klystron amplifier operating at 94 GHz. The proposed configuration accrues the advantages of both the photonic band-gap structure (facilitating larger transverse dimensions and larger beam tunnels through its defects) and the multiple-beam operation (could support multiple beam-lets through multiple-defect-tunnels with larger beam diameter for injecting higher beam current at lower beam voltage requiring reduced focusing magnetic field). However, the engineering aspects like thermal management and the mechanical alignment still need to be addressed while configuring a device using this concept. The W-band device has been designed to support six circular electron beams each carrying beam current of 300 mA at the accelerating potential of 17.5 kV. Interaction is supported through a six-cavity RF interaction structure comprising an input cavity, four buncher cavities and an output cavity.

Corresponding author
e mail: vbhanunaidu@gmail.com (Vemula Bhanu Naidu)

The manuscript is organized in five sections. The relevance of the study is introduced in Section 1. Section 2 describes the configuration of the extended interaction cavity including the coupler, Section 3 describes the PIC analysis and the study is concluded in the Section 4.

2 Extended interaction cavity

The basic photonic band-gap cavity is considered to be comprising of two-dimensional photonic crystals with the artificial defects acting as standing-wave resonators. A typical six-defect PBG configuration is shown in Fig 1 with six rods having removed from the lattice to form the defects. The multi-defect structure is formed with 6-defects in coupled form in order to accommodate six circular electron beam-lets over a wider transverse dimension.

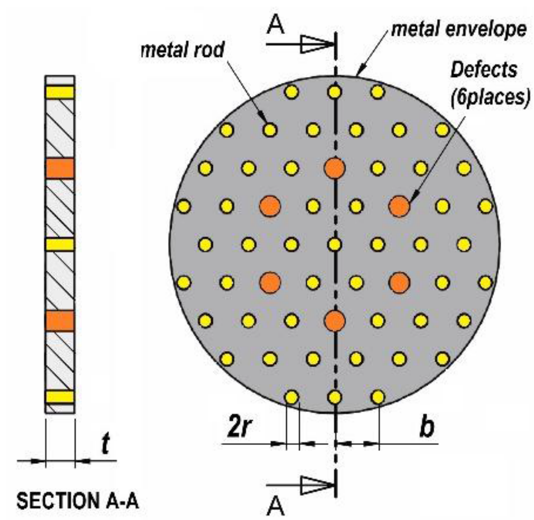
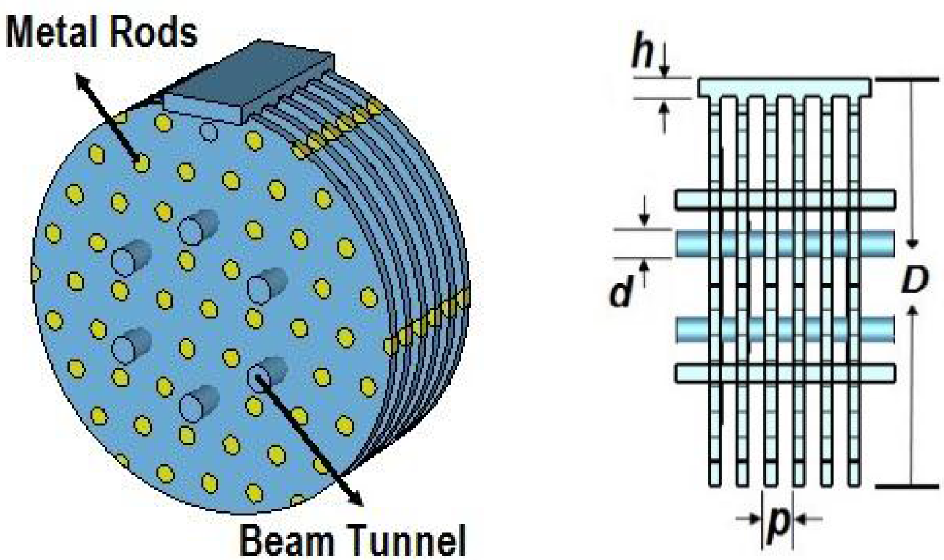


Fig 1. Schematic of a six-defect basic PBG cavity.

Table 1. Dimensions of the 6-defect EIK cavity

Parameter	Values
Radius of metallic rod (r)	0.24 mm
Spacing between rods (b)	1.32 mm
Pitch (p)	0.76 mm
Phase advance per cell	2π radian
Beam tunnel diameter (d)	0.7 mm
Envelope diameter (D)	10.5 mm
Coupler height (h)	0.1 mm

Here, r and b are the lattice parameters; r being the radius of each metallic rod and being the gap between two rods along the side of the equilateral triangle of the placement of three such adjacent rods. The parameter t is the height of the basic PBG cavity. The W-band cavity is configured using copper rods ($\sigma = 5.8 \times 10^7$ S/m) of radius $r = 0.24$ mm and cavity height $t = 0.35$ mm with the lattice constant of $r/b = 0.18$. Each of the six defects in the lattice represents an individual oscillator. Eigen-mode analysis using CST Studio shows that the weak coupling between these defects resulted in six modes namely one-monopole, two-dipoles, two-quadruples and one-sextuple in the structure depending upon the direction of the axial (z-directed) electric field. Six such PBG-based individual resonators are then cascaded to get an extended interaction cavity (EI-cavity) structure as shown in Fig 2. Dimensions of an EI-cavity are given in Table 1. The extended interaction cavity requires to be operated at the 2π-mode (the phase-advance per period in the extended interaction cavity is 2π for which the effective characteristic shunt impedance is the maximum), which is governed by the structure periodicity τ. The extended interaction cavity structure is enclosed in a metal envelope of diameter D. The SWS is optimized for operating in-like mode with 2π phase advance per period at the operating frequency of 94 GHz for beam voltage of 17.5 kV.



(a) (b)

Fig 2. Schematic of a 6-defect EIK PBG cavity buncher cavity (a) isometric view and (b) side view.

Table 2. Cavity parameters for different modes

Mode	Frequency (GHz)	(R/Q) in Ω	$(R/Q)\ M^2$ in Ω
Monopole	94	252	57.12
Dipole	95.32	28	0.63
Quadruple	98.13	17.43	0.5229
sextuple	99.91	2.64	0.264

Table 3. Mode performance of the cavity

Parameters	Values
Monopole mode	94 GHz
Q_{ohmic}	1956.97
$Q_{external}$	977.80
Q_{loaded}	653.14
3 dB Bandwidth	158 MHz

The EIK structure comprising an input cavity, four numbers of buncher cavities and an output cavity in which the waveguide type input or output-coupling is designed to take excitation from TE_{10} waveguide mode to TM_{01} -like mode in the PBG defect site (Fig 3). The coupler couples four distinct modes as shown in Table 2 and the performance for the monopole mode is summarized in Table 3. The time-domain simulation results are shown in Fig 4. The Axial (z-directed) electric field depicting the mode-pattern of the cavity is shown in Fig 5. The characteristic shunt impedance (R/Q), coupling coefficient (M) and effective characteristic shunt impedance $((R/Q)M^2)$ values are also given in Table 2. It may be noted from the values of both (R/Q) and $((R/Q)M^2)$ that contribution of other modes except the monopole mode would be negligible in the electron-wave interaction process.

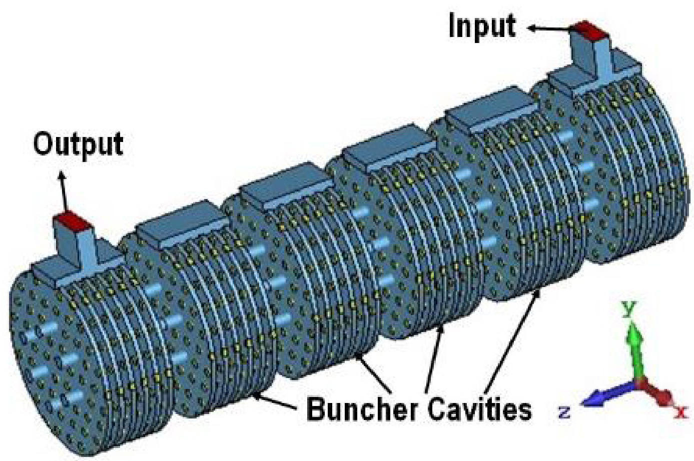


Fig 3. Configuration of the four buncher cavity EIK

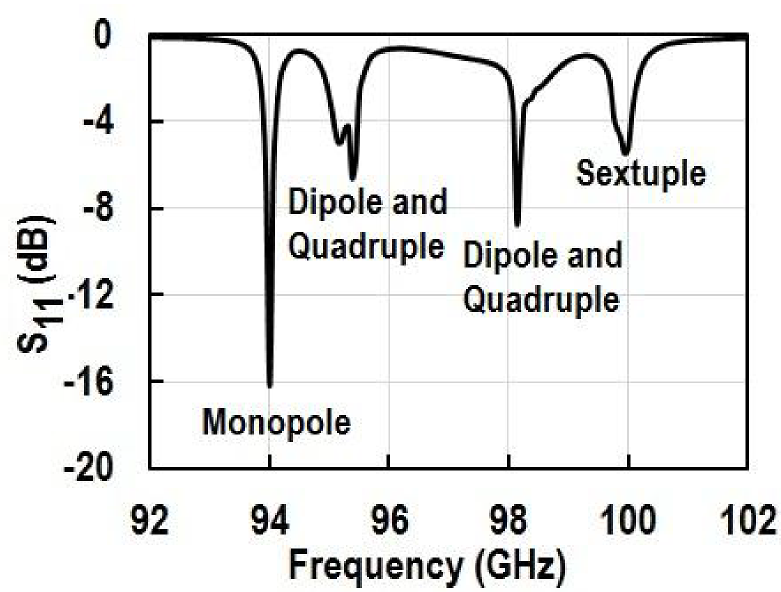


Fig 4. Time domain simulation results of the EI cavity.

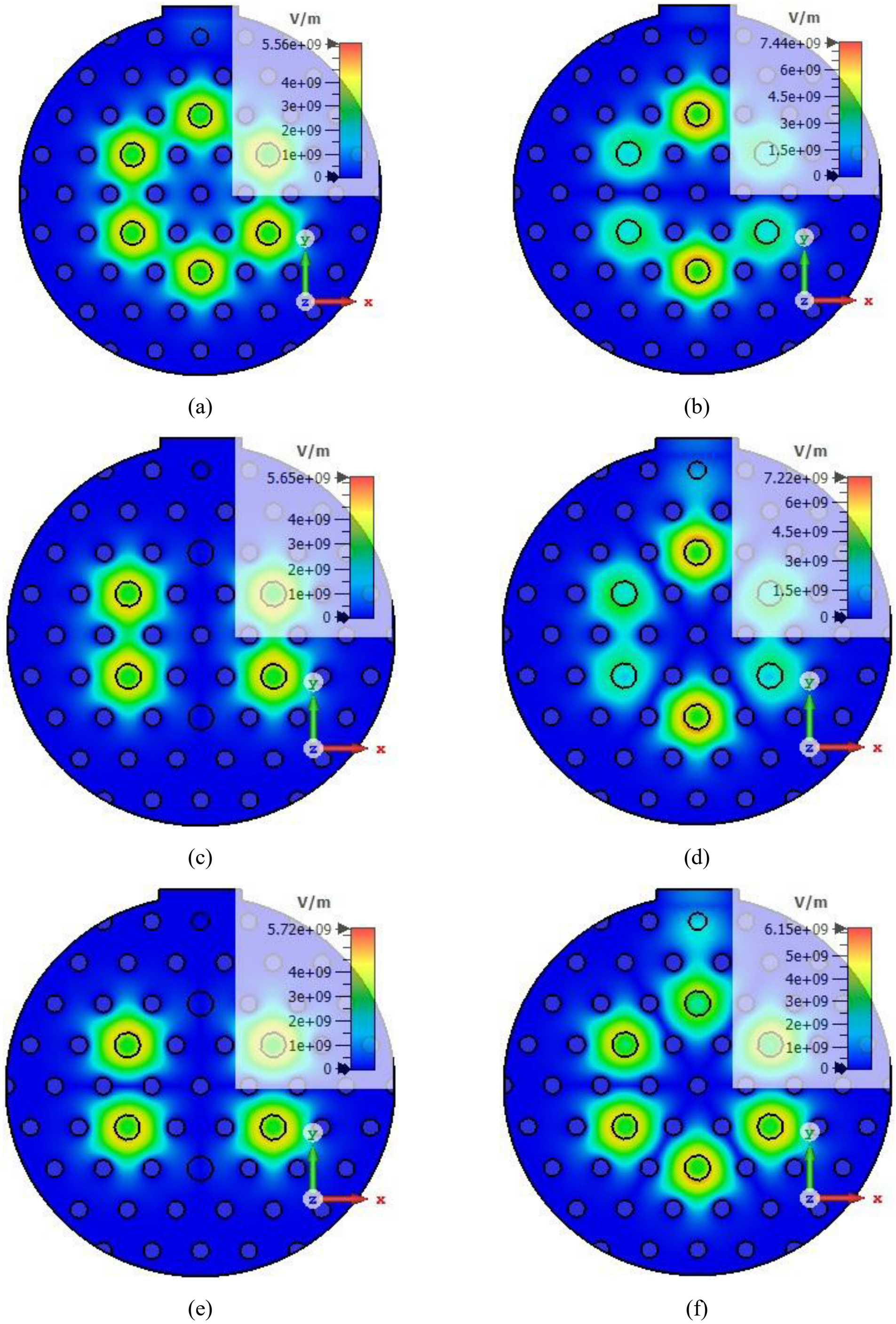


Fig 5. Axial (z-directed) electric field depicting the mode-pattern of the cavity (a) monopole at 94 GHz, (b) dipole at 95.29 GHz, (c) quadruple at 95.32 GHz, (d) dipole at 98.10 GHz, (e) quadruple at 98.13 GHz and (f) sextuple at 99.91 GHz.

3 Particle-in-Cell Analysis

The EIK structure comprising an input cavity, four numbers of buncher cavities and an output cavity is shown in Fig 2. The input and output cavities are chosen to be identical as designed in section 2. The buncher cavities are formed by shorting the waveguide coupling port of the EI-cavities. The EIK is analyzed with beam parameters of 17.5 kV carrying beam current of 300 mA in each of the six beam-lets. Modeling and the PIC analysis are carried out through CST-Studio [6]. A constant magnetic field of 0.4 T is used in the simulation. The final analysis parameters are summarized in Table 4. The analysis was carried out for the condition of saturated output power at the output port at the operating frequency of 94 GHz. The growth of electric field along the length of the interaction structure, saturated output power and the corresponding frequency spectrum are shown in Figs 6(a), (b) and (c). The transfer characteristics of the device for the monopole mode are shown in Fig 6(d).

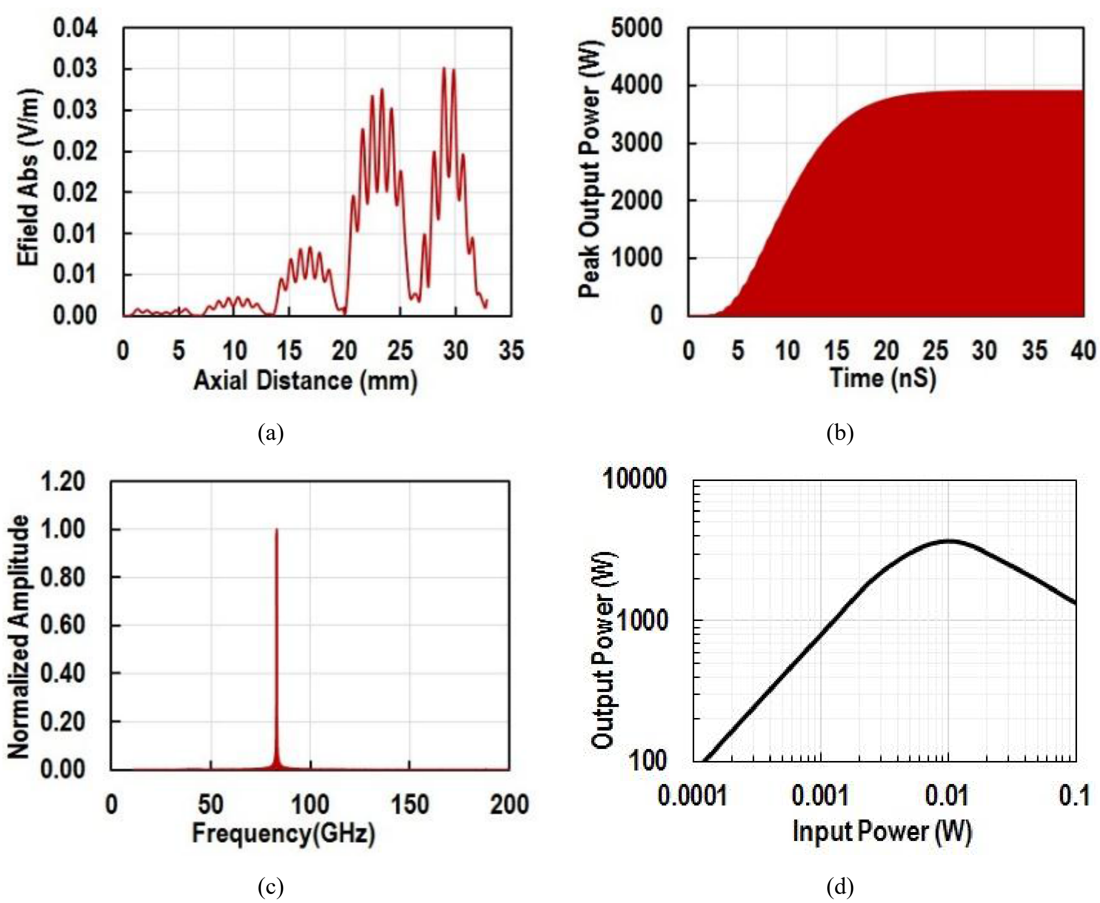


Fig 6. Particle-in-cell analysis results: (a) Growth of axial electric field along the length of the interaction structure, (b) saturated peak output power at the output port, (c) the corresponding frequency spectrum, and (d) the transfer characteristics for monopole mode operation.

Table 4. Parameters of Extended interaction klystron

Parameter	Value
Beam radius	0.22 mm
Spacing between the cavities	6.5 mm

Beam Voltage	17.5 kV
Beam current per beam-let	0.3A
Waveguide Coupler	WR10
Frequency of operation	94 GHz
(R/Q) for buncher cavity	252

4 Conclusion

Feasibility of a photonic band-gap (PBG) based multiple-beam extended interaction klystron amplifier has been explored analytically through 3D electromagnetic simulation. An extended interaction klystron structure operating around-94 GHz has been designed and analysed through PIC simulation for 6-beam operation. Particle-in-cell simulation promises peak output power of about 3.7 kW with gain of about 55 dB, hot 3 dB bandwidth of about 0.17% and electronic efficiency of around 11.7%.

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Vemula Bhanu Naidu received the B E degree in electronics and communication engineering from the Army Institute of Technology, Pune, India, in 2002. He is currently a Scientist with the Microwave Tube Research and Development Centre (MTRDC), DRDO, Bengaluru, India. His current research interests include studies on electromagnetic wave propagation in microwave circuits and computer-aided design of microwave tubes.

Dipanjan Gope received the B Tech degree in electronics and electrical communication engineering from IIT Kharagpur, India, in 2000; and the M S and Ph D. degrees in electrical engineering from the University of Washington, Seattle, WA, USA, in 2003 and 2005, respectively. He is currently an Associate Professor with the Department of Electrical Communication Engineering, Indian Institute of Science, Bengaluru, India. His current research interests include computational electromagnetics and electromagnetic interference (EMI)/electromagnetic compatibility (EMC).

Subrata Kumar Datta received the B E degree in electronics and telecommunication engineering from the Bengal Engineering College, Shibpur, India, in 1989; and the M Tech and Ph D degrees in microwave engineering from the IIT-BHU, Varanasi, India, in 1991 and 1999, respectively. He is currently the Centre Head for Microwave Tube Research and Development Centre (MTRDC), DRDO, Bengaluru, India. His current research interests include vacuum electronic devices and electromagnetic wave propagation in conventional and unconventional media.