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European Journal of Advances in Engineering and Technology, 2015, 2(10): 66-69

Research Article ISSN: 2394 - 658X

Particle-in-Cell Simulation for W-Band Power Combiner Multi-Beam Planar Coupled-Cavity Backward Wave Oscillator

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ABSTRACT

Initially, a design study is presented for a W-band planar coupled-cavity backward wave oscillator at 94.5 GHz. It is numerically simulated using CST particle-in-cell (PIC)-3D simulator and same design validated with another PIC-3D code. Further, output powers of several BWOs combines in a typical manner which resulted power multiplication order of 2.5 times and electronic efficiency multiplication almost order of 1.25 times. The in-depth particle-in-cell simulations were performed for proving the proposed novel concept.

Key words: Power multiplier, planar coupled-cavity, backward wave oscillator, W-band

INTRODUCTION

For the potential applications in the fields of sensing and communication, still vacuum electronic and MMICs communities looking for 100's watts peak power radiation sources at W-band (75-110 GHz) spectrum [1]-[3]. Specially, frequency from 80-100 GHz gives optimal channel capacity for all weather tactical communication with high data rate communication between unmanned aerial vehicles and satellites.

The state-of-the-art MMICs based oscillators are provided peak output power less than 50 mW at W-band and GaN based power amplifier module reported a record 842 mW peak output RF power at 88 GHz [4]. Compared to the others MMICs sources, vacuum electronic devices (VEDs) are dominating in the above electromagnetic spectrum mainly because of pulse/ continuous wave operation of these devices with high power and high efficiency [5]. The reported vacuum electronic oscillator provides peak power 10's watts near 95 GHz [6]. VEDs power decrease inversely proportional to the square-root of frequency. Thus, at W-band and higher frequencies, there is vital need of radiation sources which can provide peak rf-power more than 100's watts for long-range high-data-rate communications. Recently, reported design study to increase device power using multi-stage cascade TWT amplifier at 220 GHz [7].

In this paper to increase the source power a novel design concept 'power combining via cascaded backward wave oscillator (BWO)' at 94.5 GHz was reported. Primarily, design of a planar coupled-cavity (CC) BWO with cylindrical electron beam has been simulated at 94.5 GHz using CST PIC-3D code [8]. Further design was validated with another PIC-3D code [9]. This type of coherent radiation sources provides rf-power in 10's watts because of inherent limitation of oscillators [10]. Later in this paper concept of increasing the output power and electronic efficiency using typical design of cascaded BWOs was discussed. The one of the merits of this design, it is compatible with micro fabrication techniques (UV-LIGA and DRIE), so mass-production of devices are possible even at W-band and higher frequencies [11-12].

DESIGN AND COLD- SIMULATIONS

The schematic cross-section views of two-period planar CCBWO for electrostatic cold-simulation (in absence of electron beam) is shown in Fig. 1(a). The slow-wave structure (SWS) was synthesized for aiming the induced EM wave interaction with electron beam in 'velocity synchronism' condition. Initially, the cavity period 'p = (cav_l+slot_l)/2' of 0.84 mm was estimated from phase-shift 'φ' ($=k_xp$) = $(2\pi f_c/v_e)$ p, where, $\varphi = 5\pi/2$, $f_c = 94.5$ GHz, $v_e = \beta c = 0.21c$ (V_b =12 kV). Here, 'β' relates with relativistic energy factor 'γ' = $1+ eV_b/m_ec^2 = (1-\beta^2)^{-1/2}$; e and m_e represent the charge and rest mass of electron, respectively. The coupled-cavity wall-thickness 'slot_l' was chosen one-fourth of the cavity period 'p'. Later, cavity height 'cav_h' and cavity half-depth 'cav_w/2' values were synthesized which almost half and double of cavity period 'p', respectively. Finally, synthesized design parameters have been optimized using eigen-mode solver [8] to resonate this planar coupled-cavities structure at phase-shift $5\pi/2$ for electron beam voltage 'V_b' 12 kV [Fig 1(b)]. The optimized design parameters have been tabulated in Table 1. Inset figure 1(b) verified the electric field pattern for the cavity mode at phase-shifts $5\pi/2$. The square electron beam tunnel dimensions (bt_a and bt_a) were decided with intending the beam-filling factor ~ 50% for efficient beam and rf-wave interaction.

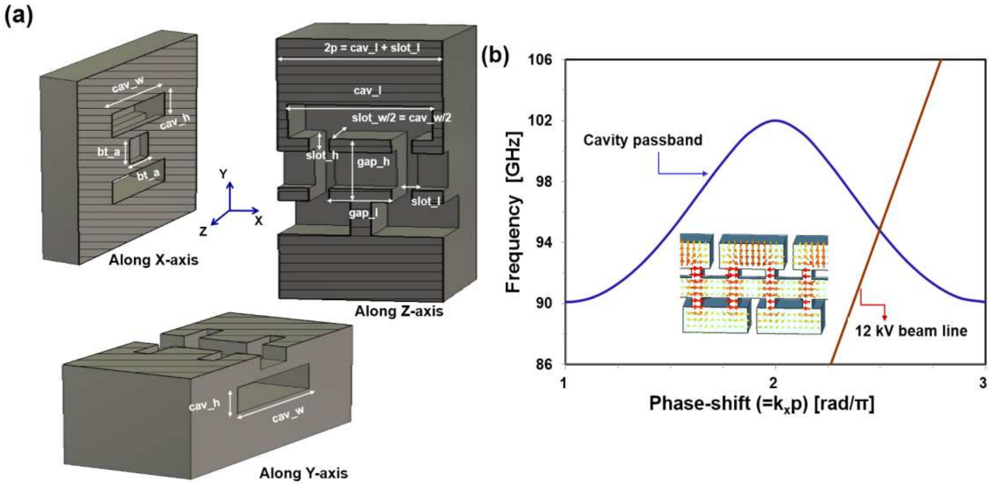

Table 1 - Design parameters of the planar CCBWO

Parameter	Value (mm)
bt_a	0.56
cav_h	0.57
cav_w	1.7
cav_l	1.47
gap_h	0.98
gap_l	0.63
slot_h	0.21
slot_l	0.21

Fig. 1 Planar CCBWO: (a) Schematic cross-section views of two period structure, and (b) numerically analyzed dispersion characteristic

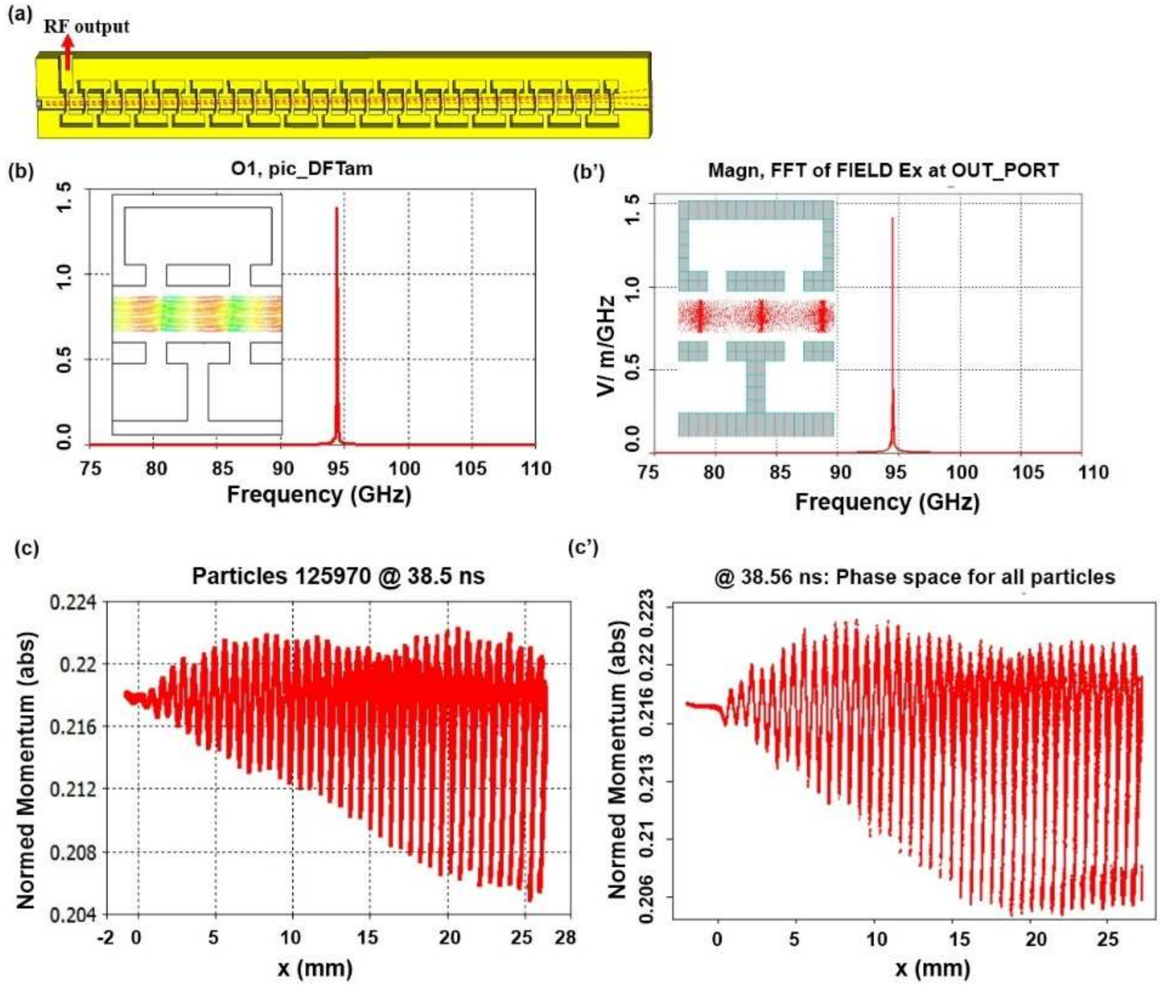

Fig. 2 (a) Schematic half cut-view of planar CCBWO simulation model PIC-3D hot-simulation results: CST's (b) electric-field amplitude, (c) normed momentum plot, and (d) saturated output power vs. time, results are agreed well with another PIC-3D code results (b'), (c'), and (d') results, respectively

HOT-SIMULATIONS FOR SINGLE CCBWO

Hot-simulations (in presence of electron beam) were performed for same planar CCBWO [Fig. 2(a)] for mainly estimating the device saturated output power. These numerical simulations were based on self-consistent finite-difference-time-domain (FDTD) PIC-3D techniques.

The electron beam of voltage 'V_b' 12 kV and current 'I_b' 0.1 A were generated from emitter radius of 0.18 mm. Afterward beam has been transported through square beam-tunnel under applied optimum uniform axial magnetic field ~ 0.21 T. Finally it dumped into collector which was electrically isolated with SWS. The minimum required axial brillouin-flux 'B_B' was calculated $B_B \geq 0.83\times10^{-3} r_b\ I_b^{0.5}/V_b^{0.25}$ T, where r_b is the beam radius. The transported electron beam was started bunching after 5 nano-sec (ns) along the beam-propagation axis [Inset Fig. 2(b) and Fig. 2(bˈ)]. At desired frequency 94.5 GHz, single electric field amplitude observed throughout the simulated W-band spectrum [Fig. 2(b)]. In phase-space, axial momentum of electrons with respect to beam propagation distance for 125970 particles @ 38.5 ns was showed energy transfer from electron-beam to backward wave at steady state condition [Fig. 2(c)]. The optimized thirty periods length of discussed SWS was provided saturated output power around 47 watts after 20 ns simulation time [Fig. 2(d)].

Later, same simulation model was simulated by applying similar simulation conditions in another standard PIC-3D code for validating the CST PIC-3D results. The second PIC simulator was showed single electric-field peak of 1.4 V/m/GHz at desired frequency 94.5 GHz [Fig. 2(bˈ)], which was well matched with CST result [Fig. 2(b)]. In addition, simulated output power result [Fig. 2(dˈ)] was also agreed well with CST result [Fig.2(d)]. Both plots were showed that rf-power start growing after 10 ns, reached at saturation ~ 22 ns, and finally obtained same saturated power ~ 47 watts.

HOT-SIMULATIONS FOR CASCADED CCBWOs

Now, power multiplication concept can be proven with cascading the planar CCBWOs in typical manner [Fig. 3]. One-by-one additional BWO's rf-output port was cascaded with previous BWO's first cavity. Each BWO is having separate electron beam of 12 kV and 0.1 A with common electron gun header and common collector for dissipating the spent electron beams. Thus, this multi-beam cascaded BWO was showed clearly efficient backward wave propagation and power combining mechanism between cascaded BWOs [Fig. 4(a)]. The phase-momentum plot for 4-beams has been clearly shown the equal-generically bunched electrons with bunching wavelength (λ_e) ~ 672 µm, which corresponds to phase-shift $5/2\pi$ mode for desired backward wave interaction [Fig. 4(b)]. Moreover, the inset figure was showed the single electric field amplitude at operating frequency 94.5 GHz.

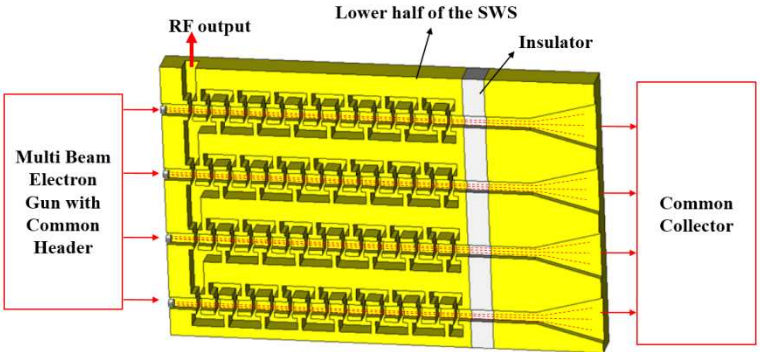

Fig. 3 Schematic half cut-view conceptual diagram of 4-electron beams cascaded planar CCBWO at 94.5 GHz

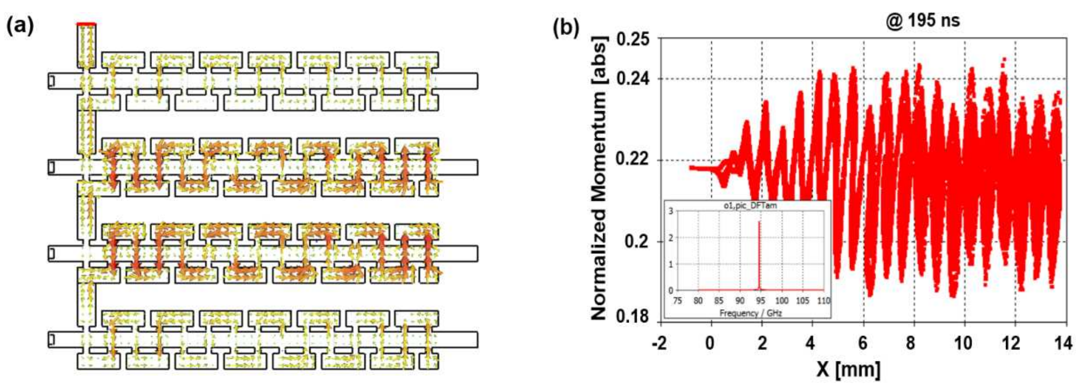

Fig. 4 Cascaded 4-BWOs: (a) simulated view of backward wave propagation and power multiplication, and (b) phase-momentum plot for 4-beams with resultant single electric-field amplitude at 94.5 GHz (inset figure)

Further, in cascaded 4-BWO concept, the numerically analyzed results were showed that optimized SWS length becomes almost half compare to the single BWO SWS length for getting steady-state saturated output power [Fig. 5(a)]. In addition, by cascading one BWO with another in opted manner, the simulated device RF-power increased by the factor of 2.5 times and electronic efficiency increased by almost 1.25 times [Fig. 5(b)]. The reason behind this power multiplication was energy inducement of circuit-wave by cascading the similar phase velocity-modulated backward wave energies. The single BWO PIC-3D results were showed saturated rf-power around 47 Watts and device electronic efficiency almost 4% at 94.5 GHz [Fig. 2(d)]. In other hand, combined 4-BWO model was showed simulated peak rf-power almost 350 watts in steady-state condition and device electronic efficiency ~ 7.5% at 94.5 GHz. This numerically analyzed planar power combiner multi-beam BWO radiation source confirmed power multiplication factor increment linearly with increasing number of BWOs, but device electronic efficiency increment was almost going to saturate up to cascading 4-BWOs [Fig. 5(b)].

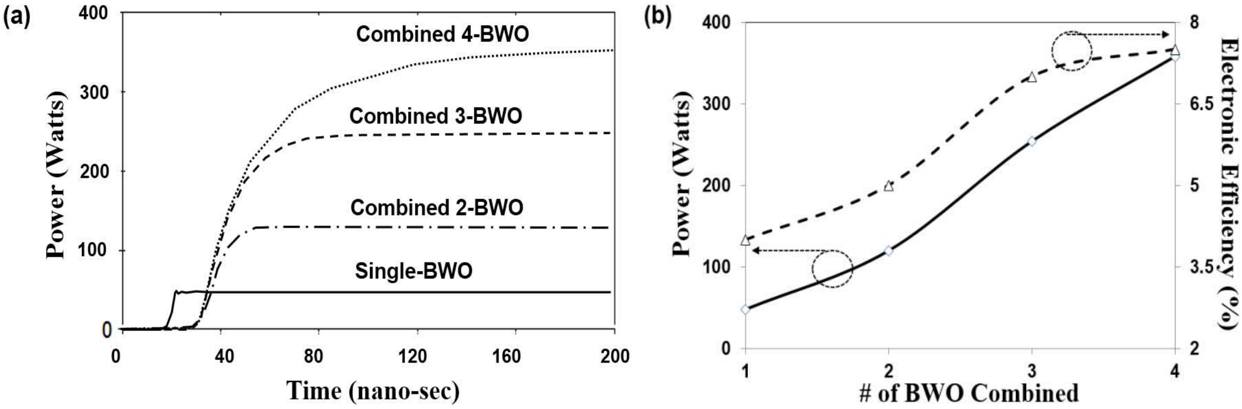

Fig. 5 (a) Numerically simulated graph for power vs. time, and (b) numerically analyzed graph for saturated rf-power and electronic efficiency (%) enhancement vs. number of BWO combined

CONCLUSION

In summary, the simulation results of novel design concept for multi-beam power combiner planar CCBWO at 94.5 GHz are very promising. This numerically analyzed source power increases in multiple of 2.5 and device electronic efficiency increases in multiple of 1.25 times. In addition, it require almost half beam-wave interaction length compared to single BWO for getting saturated rf-power. Hence, resultantly it is capable to generate high power and high electronic efficiency in compact module. In addition, this planar design conception is compatible with microfabrication techniques for 'mass-production of the device on chip'. Finally, this type of mobile high power 100's W coherent radiation source is one of the promising candidates in W-band and THz frequency spectrum to fulfill the needs mainly in the field of phase-array radars, missile seekers, and contraband imaging applications.

Acknowledgements
The authors would like to thank Director, MTRDC and Dr K S Bhat, MTRDC for their encouragement to carry out this study and permission to publish this work.

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