Compact and High-efficiency Metamaterial Extended Interaction Oscillator

Xin Wang[a], Hengyu Luo[a], Xuanming Zhang[a], Tao Tang[a], Zhanliang Wang[a], Huarong Gong[a], Yubin Gong[a], Baidyanath Basu[b], and Zhaoyun Duan[a*]

[a]School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China
[b]Sir J. C. Bose School of Engineering, Supreme Knowledge Foundation Group of Institutions, Mankundu 712139, India
*Corresponding author's email: zhyduan@uestc.edu.cn

Abstract: *A highly efficient and compact metamaterial extended interaction oscillator (MEIO) is characterized and designed. The power exchange function of the multiple-gap extended interaction resonant cavity loading the proposed metamaterial is investigated for the π mode. Furthermore, the cavity diameter of 5-gap MEIO is only 37 mm at S-band. The CST PIC simulations show the peak output power of about 10 MW and the electronic efficiency up to 48% at 2.866 GHz when the beam voltage and current are 130 kV and 80 A, respectively, and the focusing magnetic field is 2000 G. The simulation results suggest that the proposed MEIO has the potential application in the future accelerators as an MW-level high-efficiency, miniaturized microwave source.*

Keywords: metamaterial (MTM), extended interaction oscillator (EIO), miniaturization, high efficiency

Introduction

Metamaterial (MTM) is an artificially synthetic sub-wavelength structure, which can be engineered to have some unique electromagnetic properties not generally found in nature [1-3]. In recent years, the sub-wavelength below-the-cut-off waveguide resonators were used to provide negative effective permittivity and permeability by loading them with MTM units, such that they could transport TE-like and TM-like modes [4]. For instance, by using the TM-like mode, one can use MTM loaded waveguide resonators excited in the TM-like mode in vacuum electron devices (VEDs) such as travelling-wave tube, back wave oscillator, klystron, and accelerator. In fact, there has been a recent surge to explore the MTM assistance in the performance improvement of VEDs in terms of miniaturization, high efficiency, high power, dual-band operation, and so on [5-7].

In 2015, Duan *et al.* [5] reported an all-metal MTM slow-wave structure (MSWS) and established the advantages of its used in a VED in terms of the miniaturization and high efficiency of the device. At the same time, the Massachusetts Institute of Technology research group experimentally obtained 5 MW output power at 2.4 GHz [6]. In 2019, a novel all-metal MSWS suitable for high-power microwave sources by He *et al.* reporting an enhancement of the conversion efficiency up to 55.8% with an average output power of 460 MW at the L-band [7]. However, to the best of the authors' knowledge, the MTM based extended interaction devices encompassing MTM extended interaction oscillation (MEIO) have not been reported yet. This paper presents the preliminary findings of a compact, high-efficiency MEIO and predicted its performance by theory and PIC simulation.

This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grant numbers 61871095, 61921002, and 61531010.

Electromagnetic Properties of the MTM Extended Interaction Resonant Cavity

MTM extended interaction resonant cavity (MEIRC) can be considered as equivalent to an MSWS with closed ends, which supports a standing wave instead of a travelling-wave field-for interaction with an electron beam. Thus, a strong electric field exists in an MEIRC leading to a shorter longitudinal length and higher conversion efficiency as well as smaller sizes of an MEIO using such a structure.

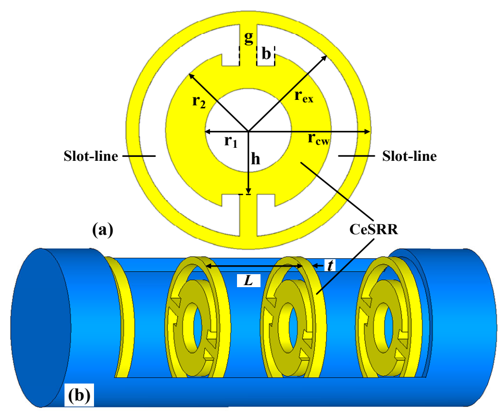

Fig. 1. (a) CeSRR unit and (b) MEIRC.

A complementary electric split-ring resonator (CeSRR) (Fig. 1(a)) and a 3-gap MEIRC loaded by CeSRRs (Fig. 1(b)) have been designed at the operating frequency 2.86 GHz setting the structure parameters as r_1=6.5 mm, r_2=12 mm, r_{ex}=16.5 mm, r_{cw}=18.5 mm, g=2.6 mm, b=3 mm, t=2.5 mm, and h=9.5 mm. Based on this design, a multi-gap MEIRC is investigated. The resonant structure can operate at the oscillation or amplification regimes depending on the values of the transit angle θ (= βL, β being the phase constant and L the axial period), according as $F_N(\theta)<0$ or $F_N(\theta)>0$, where $F_N(\theta)$ is the power exchange function of an N-gap MEIRC [8].

It can be seen from Fig. 2, for a multiple-gap MEIO operating in the π mode at 2.86 GHz, that, as the value of θ grows, the value of $F_N(\theta)$ fluctuates and, at an optimum value of $F_N(\theta)$ maximizes corresponding to a strong beam-wave interaction. Thus, we have found the optimum value of gaps N = 5 for the maximum value of $F_N(\theta)$, and hence the maximum conversion efficiency at a value of θ = 2.7 rad, taking the optimized period of MEIRC as 27 mm when the beam voltage is 130 kV.

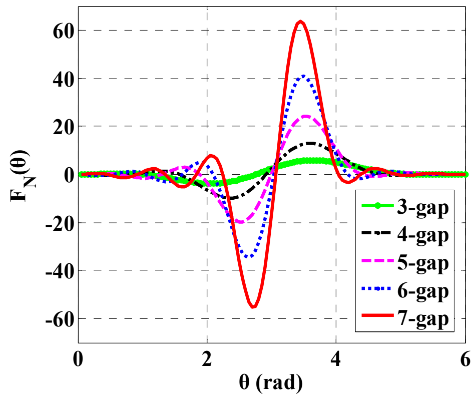

Fig. 2. Plots of $F_N(\theta)$ of a multiple-gap MEIO.

PIC-Simulation Results and Discussion

Fig. 3 shows the 5-gap MEIO (N = 5) with standard rectangular waveguide coupling through BJ32, setting the coupling port at W_{ca} = 54 mm and W_{cb} = 24.5 mm, with the length L_0 optimized to the value of 21.5 mm. The number of gaps N = 5 is optimally chosen to ensure the realization of maximum output power noting that the increase of N beyond 5 would cause a backflow of electron beam causing a decrease in the output power.

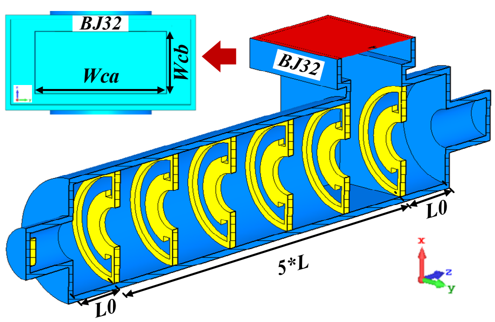

Fig. 3. Schematic of the 5-gap MEIO.

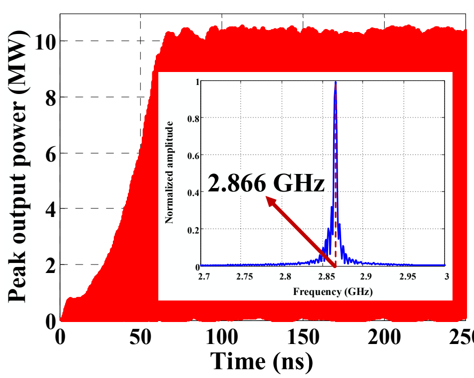

Fig. 4. Peak output power and spectrum of the output signal.

After completing the schematic design of the 5-gap MEIO, the beam-wave interaction simulation is carried out by using CST Particle Studio. The beam voltage and current are taken as 130 kV, 80 A, respectively, and the focusing magnetic field of 2000 G is adopted. The radius of the electron beam is 4.45 mm, and the channel radius is 6.5 mm.

The PIC simulation results are shown in Fig. 4. The peak output power of the 5-gap MEIO is about 10 MW, corresponding electronic efficiency is 48%, and the signal gradually reaching stability after 80 ns. The signal spectrum shows the central frequency is 2.866 GHz, and the waveguide coupler ensures that the MEIO has a power capacity of MW-level. Furthermore, the peak output power and efficiency versus gap number plots are shown in Fig. 5.

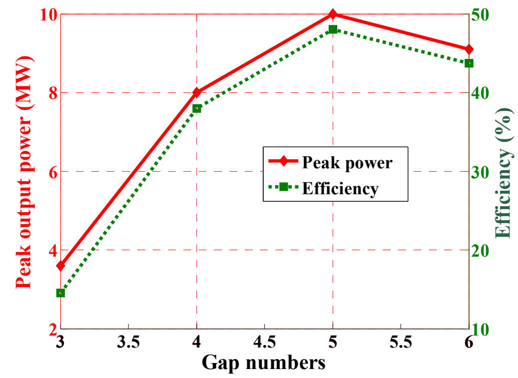

Fig. 5. Peak Output power and efficiency versus gap number plots of MEIO.

Conclusion

The design of a compact and high-efficiency 5-gap MEIO with a waveguide coupler is proposed. Especially, the transverse inner diameter of the MEIO is found to be only 37 mm and the longitudinal length is about 180 mm. The beam-wave interaction study predicts the peak output power of about 10 MW and electronic efficiency up to 48% at 2.866 GHz by using CST PIC simulation under the condition of beam voltage 130 kV, beam current 80 A, and focusing magnetic field of 2000 G. These results clearly indicate that the proposed compact, high peak power, and high-efficiency MEIO can be used as the MW-level microwave source having potential applications such as in the future accelerators.

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