A 3D-Printed Metamaterial Slow Wave Structure for High-Power Microwave Generation

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Abstract*: *We present a high power microwave (HPM) source based on a metamaterial slow wave structure (MSWS). The MSWS is composed of a circular waveguide with periodic loading of two complementary split-ring resonator disks and was designed at the University of California, Irvine (UCI). This SWS has been studied and simulated to quantify its cold structure properties. Moreover, a backward wave oscillator (BWO) using the proposed SWS has been simulated using a particle-in-cell solver to evaluate its performance. In simulations this BWO has generated 88 MW peak power in a pulse duration on the order of 15 ns with frequency about 2.9 GHz. This SWS was fabricated using 3D printing and copper plating technology and was tested using the SINUS-6 pulsed electron beam accelerator at the University of New Mexico (UNM). This paper presents the results.

Keywords—slow wave structure (SWS); backward wave oscillator (BWO); metamaterial; high power microwave (HPM)

I. Introduction

HPM generation using relativistic electron-beam driven vacuum devices is considered the sole technology for generating mega- and giga-watts of power used in radars, satellite communications, and various other applications [1]. We are investigating means to improve the HPM generation efficiency using an all-metal left-handed material SWS. In this summary we describe a MSWS that offers good interaction impedance [2,3] in addition to its ability to exhibit a multi-mode degenerate dispersion associated with a degenerate band edge [4-6]. We present an example of the realization of a BWO based on the proposed MSWS where the cold- and hot-structure performance were evaluated using full-wave simulations. Remarkably, a 3D printed, copper plated MSWS was successfully tested using UNM's SINUS-6 pulsed electron beam accelerator.

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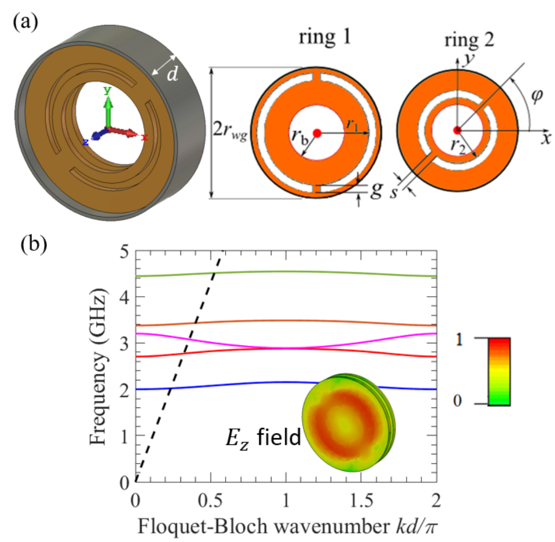

Fig. 1. (a) A periodic unit cell of the proposed MSWS: a disk-loaded circular waveguid with two misaligned CeSRRs, designed to facilitate the mode mixing required for multiple-mode interaction regime. (b) Dispersion diagram of the lowest order Floquet-Bloch eigenmodes of the cold periodic MSWS in (a). The longtudinal electric field map of the third mode (purple trace) at the transverse cross-section in the unit cell at z = *d*/2 shows that this mode has an almost TM_{01}-like mode pattern.

II. Geometry of MSWS and Simulation Results

Our MSWS is an extension of the all metal complementary electric split-ring resonator (CeSRR) that was independently studied in [3]. The main difference in our proposed MSWS is that we introduce two CeSRRs in a unit cell with two different resonant frequencies. The unit cell has period d =15 mm and is in a circular waveguide of radius r_{wg} = 25 mm periodically loaded with two circular metallic rings, each of which has a beam tunnel of radius r_b = 13 mm as well as two irises. The irises in each ring in the unit cell are in the shape of half rings. Moreover, the two irises have rings

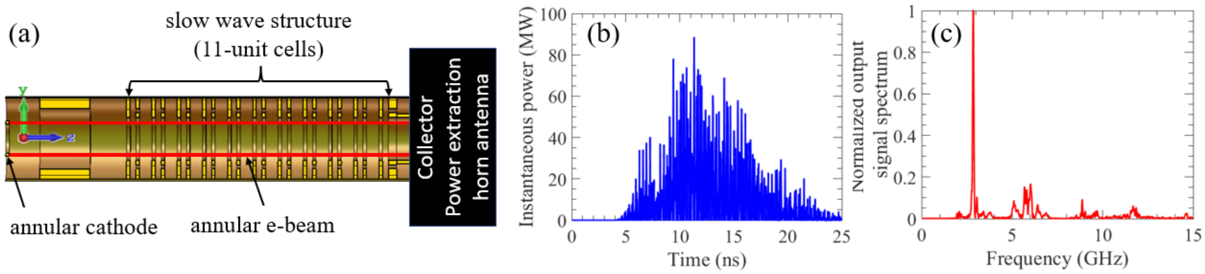

Fig. 2. (a) Schematic of the BWO structure in the *r-z* cross-section at the $x = 0$ plane. (b) Simulated output instantaneous power with a maximum around 88 MW, and (c) output spectrum obtained from a Fourier transform of the signal in the time window from 0 to 25 ns, showing a single frequency oscillation at 2.9 GHz.

of different radii, such that the inner radii of the two rings are $r_1 = 15.7$ mm and $r_2 = 20.7$ mm, respectively. The two rings are misaligned by an angle ϕ, Fig. 1(a), as a further parameter to control the modal dispersion.

In the following analysis, we assume a lossless structure, i.e., we ignore conduction loss. The ω-k dispersion diagram of the proposed structure is obtained using the eigenmode solver implemented in CST Studio Suite by DS SIMULIA and depicted in Fig. 1(b). The backward mode, i.e. the purple trace, is the one interacting with the electron beam and has a strong axial electric field (shown in the inset) to efficiently interact with the electron beam, indicating high interaction impedance, greater than 100 Ohms. The electron-beam line of 490 keV (black dashed line) is plotted, showing that the beam line intersects with the cold dispersion curves at different frequencies for each MSWS eigenmode.

To evaluate the performance of the proposed SWS, a BWO setup shown in Fig. 2(a) was simulated using the particle-in-cell (PIC) solver implemented in CST Studio Suite by DS SIMULIA. The SWS consists of $N = 11$ unit cells and the total length is 165 mm. The total length of the entire BWO structure from the cathode to the horn antenna (used to extract the generated power) is 460 mm. An annular beam with inner and outer radii equal to 8.7 and 10.5 mm, respectively, is generated using a pulsed voltage with peak amplitude 490 kV. A static axial magnetic field $B_z = 1.6$ T is used to provide confinement of the annular electron beam traveling in the axial direction.

In Fig. 2(b) we show the simulated transient output power obtained from the waveguide port monitor at the end of the SWS. The maximum instantaneous output power reported here is about 88 MW. The frequency spectrum of the output signal shown in Fig. 2(c) is obtained by evaluating the Fourier transform of the output signal shows an oscillating frequency around 2.9 GHz.

The RF conversion efficiency of 5.5% is calculated by dividing the maximum instantaneous output power by the peak input beam power. It is worth noting that the RF conversion efficiency can be improved by lowering the electron beam applied voltage. A 15% RF conversion efficiency has been observed for an electron beam applied voltage around 200 kV, with maximum instantaneous output power 25 MW.

III. Experiments

Experiments were performed using UNM's SINUS-6 electron beam accelerator and a 3D-printed, copper-plated UCI MSWS. An output power of about 22 MW at a frequency of about 3.0 GHz was observed for an electron beam energy of 490 keV. Figure 3 shows the experimentally measured frequency. Additional details will be provided at IVEC2020.

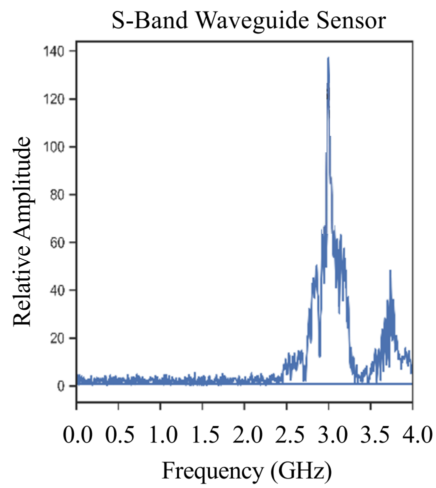

Fig. 3. FFT of the measured RF electric field output in hot test experiments. The oscillation frequency is in good agreement with the simulated one.

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