Controlled Harmonic Frequency Locking in the Harmonic Recirculating Planar Magnetron

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Abstract: *The Harmonic Recirculating Planar Magnetron (HRPM) is a novel, tunable, multi-spectral source of high power microwaves (HPM). Consisting of an L-Band Oscillator (LBO, near 1 GHz) and S-Band Oscillator (SBO, near 2 GHz), the HRPM can generate HPM at multiple frequencies simultaneously by leveraging harmonic frequency locking. In the locked state, the SBO frequency locks to the LBO second harmonic frequency. HRPM operation was characterized in simulation and experiment, with the LBO frequency and SBO quality factor (Q) as the independent variables. It is concluded that the oscillators act as a damped, driven, harmonic oscillator system, where the LBO is the driving oscillator, the SBO is the driven oscillator, and the harmonic content in the beam spokes is the coupling mechanism between them. In standard-HRPM experiments, the SBO generated 9.5 ± 1.4 MW (high Q), 19 ± 6 MW (moderate Q), and 28 ± 9 MW (low Q) in the π-mode. In isolated-SBO experiments, the output power was not significantly different, but the primary operating state was the 5π/6 mode. Therefore, implementation of the LBO enabled mode control of the SBO.*

Keywords: magnetrons; oscillators; frequency locking; frequency harmonics; electron beams; harmonic generation; RF extraction

Introduction

The magnetron is a highly efficient and compact source of microwave power that can be found in an array of applications, from industrial heating to national security. The relativistic magnetron is valuable in defense applications as a source of high power microwaves (HPM). One such example is in counter-IED (improvised explosive device) technology, where the objective is to disable or destroy the target from a safe and remote distance. An IED may be more susceptible to HPM in one frequency band than another, and it is thus beneficial to irradiate the target with HPM at multiple different frequencies simultaneously. The conventional magnetron is useful for such an application, but it is an inherently narrowband device, often designed to generate a single frequency. Investigators at the University of Michigan invented the Recirculating Planar Magnetron (RPM) [1], and its unique geometry enabled the Multi-Frequency Recirculating Planar Magnetron (MFRPM) [2]. The MFRPM can generate multiple frequencies simultaneously with, e.g., an L-Band Oscillator (LBO) and S-Band Oscillator (SBO), designed to operate near 1 GHz and 2 GHz, respectively. Furthermore, harmonic frequency locking was discovered in the MFRPM [3], where the SBO frequency locked to the LBO second harmonic frequency, resulting in more stable and consistent operation. The driven oscillator hypothesis was formed to explain this phenomenon, wherein the LBO acts as the driving oscillator, the SBO acts as the driven oscillator, and the two are coupled together by harmonic content in the beam spokes. While the MFRPM improved the state of the art in multi-spectral HPM sources, its operating frequencies were not tunable and its geometry limited it to generation of no more than two frequencies.

The HRPM and Harmonic Frequency Locking

The Harmonic Recirculating Planar Magnetron (HRPM) implements its own three-cavity LBO and six-cavity SBO and differs from the MFRPM by placing them adjacent to each other, on the same side of the cathode. Demonstrated in ***Figure 1***, the LBO interacts with and modulates the beam into spokes, generating harmonic content. The spokes then drift directly into SBO, exciting it to operate at the LBO harmonic frequency. This encourages the two oscillators to lock.

By placing the LBO and SBO on the same side of the cathode, the HRPM prototype serves as a proof of principle for a magnetron capable of generating four or more frequencies. In theory, additional slow wave structures could be placed downstream of the SBO. The smooth-bore drift region on the opposite side of the cathode could be replaced by a pair of oscillators scaled to different frequencies, or by an identical LBO-SBO pair to generate greater power.

Furthermore, the HRPM was designed to test the driven oscillator hypothesis by allowing control of two independent variables: the LBO frequency and SBO quality factor (Q). It is expected that the locked bandwidth will increase as the quality factor is decreased. Therefore, the LBO was designed with tuning rods to allow generation of a range of excitation frequencies on a shot-to-shot basis. Microwave power is extracted from the SBO using coaxial all cavity extraction (CACE) [4], where each pair of cavities couple to a single waveguide, resulting in a total of three different outputs. CACE allows variation of Q on an experiment-to-experiment basis.

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Power extraction was not implemented on the LBO due to physical constraints imposed by the test chamber.

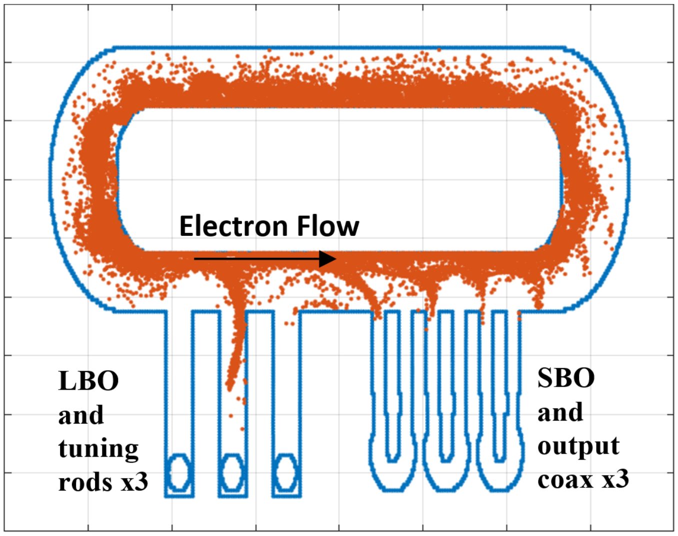

Figure 1: An ICEPIC simulation of the HRPM, demonstrating π-mode operation of the LBO and SBO.

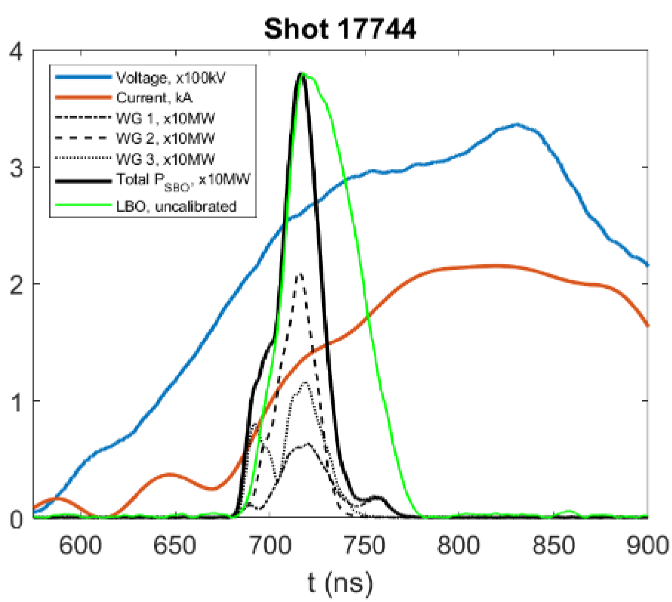

Figure 2: A sample HRPM shot, demonstrating voltage, current, output power from each SBO waveguide output, and LBO operation.

Figure 2 exhibits a sample HRPM shot, demonstrating simultaneous generation of LBO and SBO power. The SBO generated a peak power of 38 MW. Each SBO output produced maximum power concurrently, indicative of π-mode operation. The LBO signal is overlaid, retrieved with recessed B-dots in each cavity, and peaks at the same time as the SBO.

HRPM operation was characterized in simulation and experiment by varying the LBO frequency and SBO Q. In standard-HRPM experiments, the SBO generated 9.5 ± 1.4 MW (high Q), 19 ± 6 MW (moderate Q), and 28 ± 9 MW (low Q) in the π-mode. In each case, harmonic frequency locking was observed; moreover, the locked bandwidth was inversely proportional to Q across the three experiments, which is consistent with the driven oscillator hypothesis. Furthermore, the output power in isolated-SBO experiments was not significantly different from standard-HRPM experiments; however, the $5\pi/6$ mode was dominant in the majority of isolated-SBO experiments. This demonstrates that the addition of the upstream LBO provides mode control over the SBO. Finally, a reverse magnetic field experiment was performed to further examine if the locked state is due to the beam spokes. By circulating the electron hub/spokes from SBO to LBO, the locked state was significantly diminished.

Going forward, phase analysis of the LBO and SBO signals will be completed to determine whether the LBO and SBO demonstrated harmonic phase locking, which was not shown in the MFRPM. Future experiments will consider the possibility of standard-HRPM operation at SBO quality factors lower than what can be achieved in isolated-SBO experiments [5], where the LBO modulated beam enables the SBO to achieve startup despite operating at a prohibitively low Q. This would enable generation of HPM at higher efficiencies than otherwise possible in the isolated-SBO configuration.

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