# Experimental Hot Test Results of a Metamaterial-Enhanced Resistive Wall Amplifier Prototype*

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**Abstract:** *The Metamaterial-Enhanced Resistive Wall Amplifier (MERWA) is theoretically predicted to offer high gain rates with a modest bandwidth. The MERWA operates via space charge wave growth due to interaction with a metamaterial that has been engineered to provide an inductive-resistive admittance to the edge of beam. Previous work has shown that an inductive-resistive metamaterial could be implemented using a periodic array of thin lossy wires. We have implemented and tested an experimental low-power prototype to validate the theory. This work details experimental hot test results.*

**Keywords:** Microwave amplifier; metamaterial; vacuum electron device.

The Metamaterial-Enhanced Resistive Wall Amplifier (MERWA) [1-4] has been proposed as a microwave amplifier with potential for high gain rates with moderate bandwidth. The MERWA improves performance of a Resistive Wall Amplifier (RWA) by adding an inductive metamaterial (MTM), effectively making an inductive-resistive wall amplifier. As opposed to many common amplifiers, which operate via amplification and extraction of a circuit wave, the MERWA works by amplifying the beam's slow space charge wave while the circuit wave is attenuated by loss in the resistive wall. The space charge waves must be set up on the beam by some upstream input device, and power from the amplified space charge waves must be coupled out by a downstream output structure.

Previous work [5-6] has shown that an inductive-resistive MTM to serve as a low-power prototype could be created based on a periodic array of thin lossy wires. The wires are meandered to add extra inductance and made of a lossy metal (stainless steel) to add resistance. We have successfully implemented and characterized a version of the prototype for hot test experimental validation. This work details the hot test setup and provides experimental results using the prototype.

The prototype was designed to be operated at low power due to constraints of our experimental facilities. The hot tests operated near 2 GHz with a pulsed beam having approximate parameters of 5 kV beam voltage, 0-300mA beam current, and ~1 mm beam radius.

A cross-section of a single period of the MTM meandered-wire array prototype is shown in Figure 1. The meandered-wires are 10 mm wide, 5 mm tall, 0.1 mm thick and periodically spaced 4 mm apart. A CAD diagram of the experimental prototype is shown in Figure 2 but with the metamaterial represented by a rectangular rod. The metamaterial is positioned inside a rectangular waveguide designed to be cutoff for operating frequencies of interest.

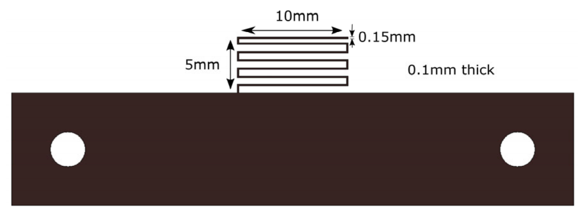


**Figure 1.** Cross-section of single period of meandered-wire metamaterial with dimensions used in experimental prototype. The bottom portion with holes is used for mounting and construction.

The MTM interaction section is 0.3 m long and positioned between two helices used to couple power into and out of the structure. The input helix, fed by a signal generator, sets up the beam's space charge waves by velocity modulating the charges before the beam passes into the MTM interaction region where the space charge wave growth occurs. After leaving the MTM interaction region, the second helix couples a portion of the power out of the beam to a 4 GHz oscilloscope where it is processed and recorded.

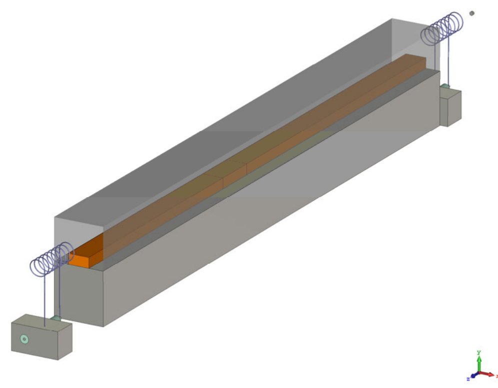

**Figure 2.** A CAD diagram of the experimental prototype with the MTM visualized using a rectangular bulk medium. The MTM is placed inside a cutoff rectangular waveguide. Input and output helices are positioned on either side to couple power into and out of the structure.

The helices were not optimized and are inefficient. For the immediate purposes of validating theories of MERWA gain, we are merely interested in evidence of growth rates rather

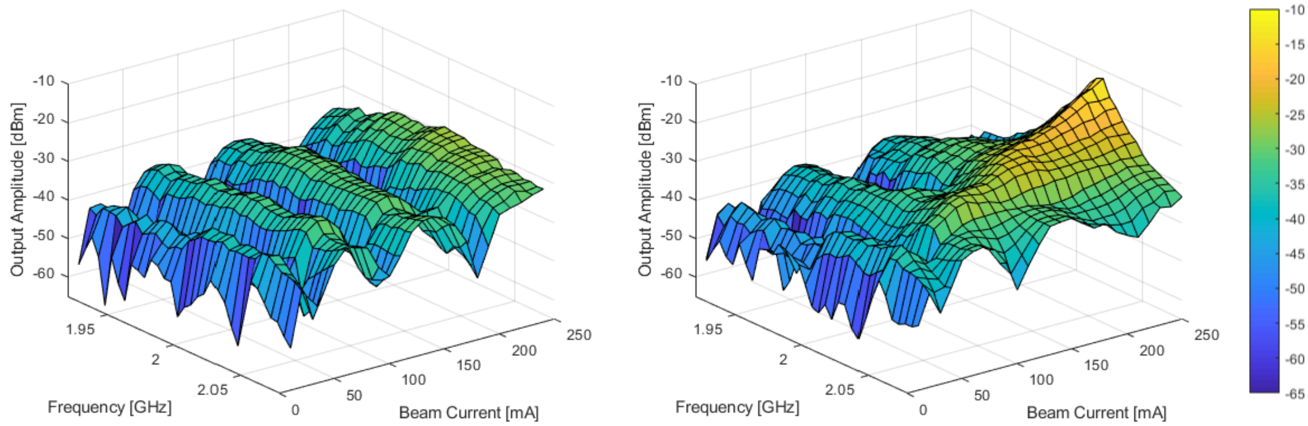


**Figure 3.** Experimentally measured output power for 5 kV beam vs. beam current and operating frequency. Each point is measured output amplitude for a beam shot using specified beam current and input frequency. Case 1 (left): Large distance between beam and MTM (7.0 mm) results in weak coupling, reveals behavior of non-growing waves as observed in a klystron amplifier. Case 2 (right): Small distance between beam and MTM (4.8 mm) results in strong coupling and significantly increased output power, indicating presence of a growing wave.

than overall device gain and the inefficiencies of the helices are not important.

To compensate for the inefficient couplers, and to calibrate out the effects and clearly show evidence of growth, we can simply alter the height of the beam above the metamaterial to control the amount of coupling between beam and circuit waves. By repeating the same measurements at two different beam height offsets we can conclusively show the MERWA MTM prototype causes growth. We simply show two cases:

Case 1: The beam is positioned far from the MTM (7.0 mm above). The beam waves and circuit do not couple strongly and the beam physics proceeds as if there is no MTM present. Charges bunch and de-bunch as if traveling through a cutoff drift tube with no exponential growth. The leftmost plot in Figure 3 shows the experimental output measured vs. frequency and beam current at a beam voltage of 5 kV.

Case 2: The beam is moved closer to the MTM (4.8 mm above). The coupling between beam waves and circuit increases significantly and MERWA space charge wave growth occurs. The rightmost plot in Figure 3 shows the output power measured from the same experiment as Case 1 repeated but with the beam moved closer to the MTM. Significantly higher output power was measured for a range of frequencies due to the increase in coupling to the MTM.

The peak increase in measured output power of approximately 15 dB between cases is directly attributable to the beam's proximity to the MTM and associated increase in coupling. Since the circuit is approximately 0.3 m long and the measured output power is 15 dB higher, we can infer that the gain rate increases by at least 50 dB/m for the peak frequency. This MERWA prototype and the experimental parameters used were not optimized for performance. Nonetheless, these hot test results indicate that the predicted phenomenon of MERWA space charge wave growth is real.

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