Experimental Demonstration of a W-band Photonic Bandgap Klystron

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Abstract: *This paper details recent progress on the experimental demonstration of a W-band klystron amplifier completed at the MIT. The amplifier utilizes a square lattice photonic bandgap (PBG) structure that permits the use of a highly oversized beam tunnel of diameter ~λ/4. Cold test measurements of the PBG klystron cavities revealed successful fabrication of the device. In hot test, a small-signal gain of 26 dB was measured at 93.7 GHz, with a saturated output power of 30 W.*

Keywords: W-band klystron, photonic bandgap klystron

Introduction

Conventional linear vacuum electron devices (VEDs) are constrained to strict frequency scaling laws, requiring circuit dimensions to scale with wavelength. In many ways, these scaling laws are the root cause for the limited availability of high power linear VEDs in the hundreds of GHz frequency range. The possibility of relaxing these constraints, holds great promise for the extension of conventional VEDs well into the terahertz band.

Experimental Setup

This study details the development of a 94 GHz extended interaction klystron with circuit features far exceeding these frequency scaling limitations. For example, in conventional VEDs, the diameter of the electron beam tunnel diameter is on the order of one-tenth of the free-space wavelength (i.e. $D_T \sim \lambda/10$). In contrast, the circuit explored here uses a 0.8 mm electron beam tunnel diameter, which corresponds to $D_T \sim \lambda/4$.

Larger circuit dimensions are also associated with additional electromagnetic modes, which could lead to mode competition or instability. To address this possibility, a mode selective PBG circuit is used. PBGs have been demonstrated in accelerator cavities and gyro-devices and have been proposed for conventional VEDs [1] although their application to conventional VEDs has been limited [2,3]. Early designs of the PBG-klystron amplifier (see refs. [4,5] were based on a 2D PBG comprised of circular conductors in a triangular lattice. That is, the circuit consisted of an iris-gap cascade along the electron beam axis, and a 2D PBG transverse to the electron beam axis (see ref. [4] for additional details).

In practice, this circuit was fabricated via first machining a block of copper with a series of slots along the beam axis, and a hole pattern for the PBG lattice transverse to the beam axis. Rods were pushed into the PBG lattice holes, resulting in the desired circuit geometry. However, poor electrical contact between the rods and the machined slots resulted in weak resonances and poor Ohmic quality factors [5].

To circumvent this issue, the device explored here utilizes a revised PBG topology consisting of a square lattice of square conductors (see also ref. [6]). Similar to the earlier design, the new circuit consists of an iris-gap cascade along the electron beam axis, and a 2D PBG transverse to the electron beam axis. However, instead of a 2D triangular

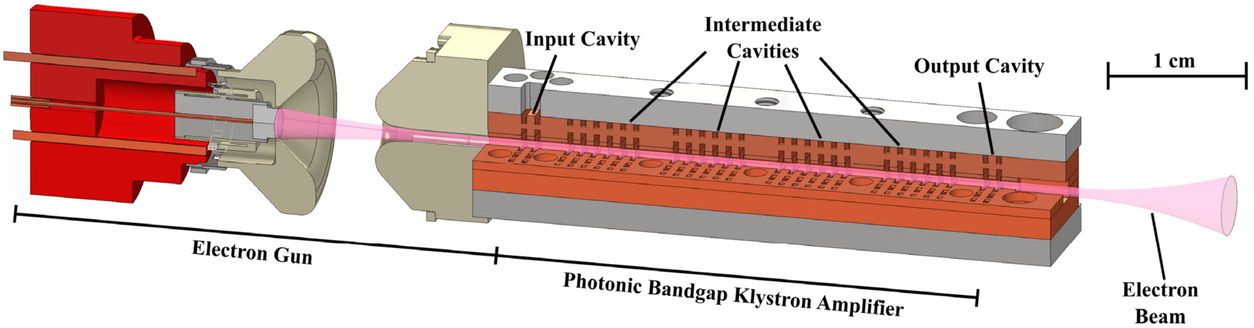

Figure 3. CAD rendering of the photonic bandgap klystron and electron gun.

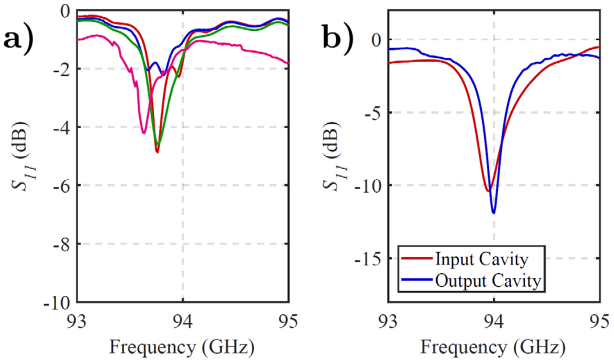

Figure 2. (a) Measured input return loss for each of the intermediate cavities. (b) Measured input return loss for the input and output cavity.

lattice of circular conductors, the PBG is a 2D square lattice of square conductors. As detailed in ref. [6], this revised topology has the advantage that the PBG elements are directly machined into the circuit. Moreover, the circuit may be fabricated in a split-block type approach, which aids in minimizing losses.

The complete klystron circuit consists of an input cavity, four intermediate cavities, and an output cavity for a total of six cavities. The input and output cavities are identical to one another, with each cavity having only two periods along the beam axis. The intermediate cavities are also identical to one another, however, they differ from the input and output cavities, as they have six-periods along the beam axis. The Pierce-type electron gun was jointly designed by MIT and Northrop-Grumman Corp. (NGC), then built at NGC. Both the klystron and electron gun are designed to operate at 20 kV and 290 mA. A 0.5 T permanent magnet is used to confine the beam.

Experimental Results

The results of cold test measurements for each of the cavities are given in Fig. 2. Note that the intermediate cavities are only weakly coupled to their waveguide ports, such that they may be cold tested without significantly reducing the effective quality factor, which would reduce the overall device gain. After machining, each cavity was “hand-tuned” to minimize cavity-cavity frequency spread. The input and output cavity both featured a strong, narrow resonance near 94 GHz, while the intermediate cavity frequencies were approximately 93.7 GHz. Also, note that Ohmic quality factors were measured to be approximately 400, which indicates that this circuit featured significantly lower loss than earlier circuits using the triangular lattice of circular conductors lattice.

Hot test results, also detailed in ref. [6], are given in Fig. 3. Although 20 kV was the nominal design voltage for the electron gun and klystron circuit, improved device performance was observed for higher beam voltages. At 23.5 kV, a peak small-signal gain of 26 dB was measured at ~93.7 GHz. At this same beam voltage, the saturated output power was measured to be ~30 W. Particle-in-cell (PIC) simulations were performed using CST Particle Studio. In PIC simulation, a device gain of 25 dB, and saturated output power of 15 W were calculated, which is reasonably consistent with experimental measurements.

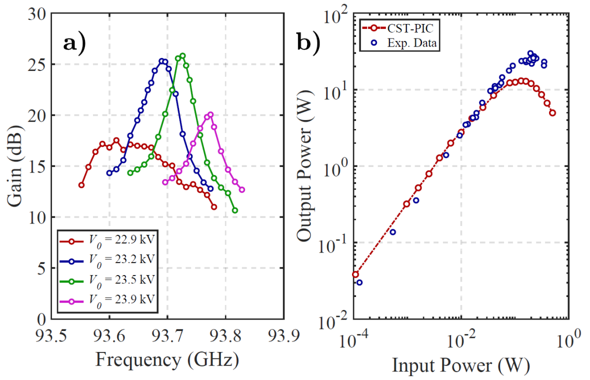

Figure 3. (a) Measured small-signal gain versus frequency for different electron beam voltages. (b) Output power versus input power at 93. 7 GHz, measured using a 23.5 kV electron beam voltage.

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