Design of a High Power S-Band Amplifier Utilizing a MTM Interaction Circuit

Electron beam simulations and MTM circuit design

FY'12 MURI
Transformational Electromagnetics

MURI TELECON
April 5th, 2013

Jason S. Hummelt
Outline

- Introduction
- 500 kV electron beam
- Metamaterial (MTM) circuit design
- Future Work
- Conclusions
Introduction

- MIT – part of the FY12 MURI
  - Experimental and theoretical research on innovative use of MTMs in continuing, controlling and radiating intense microwave pulses

- Long term experimental Goals
  - Amplifier
  - High power
  - Stability/Long pulse

- Near term goals
  - S-Band (2-4 GHz)
  - 500 kV, 80 A electron gun (40 MW beam power)
  - 1 μs pulse
  - Use of complementary split ring resonator (CSRR)
  - First design: (as presented in this talk) is a backward wave oscillator (BWO), not an amplifier
  - Future designs in collaboration with MURI team
MIT HPM Experiments

17 GHz accelerator w/ 25 MW klystron

MIT Modulator Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator Voltage</td>
<td>700 kV</td>
</tr>
<tr>
<td>Modulator Pulsed Power</td>
<td>500 MW</td>
</tr>
<tr>
<td>Beam Current</td>
<td>780 A</td>
</tr>
<tr>
<td>Modulator Pulse Length</td>
<td>1.0 μs Flat-top</td>
</tr>
<tr>
<td>Klystron Power</td>
<td>25 MW</td>
</tr>
</tbody>
</table>

Modulator V, I Waveforms

MTM Exp.

Klystron
MIT HPM Experiments

94 GHz TWT

Solenoid

Overmoded coupled cavity design

1.5 MW 110 GHz Gyrotron

Window

Superconducting Magnet

Calorimeter

Collector
BWO Design

- Beam physics
  - 500 kV electron gun

- Beam-wave physics
  - MTM circuit design

- Microwave engineering
  - Couplers, etc.

First Design: BWO
Pierce-Type Electron Gun

<table>
<thead>
<tr>
<th>Gun Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>500kV</td>
</tr>
<tr>
<td>Current</td>
<td>82A</td>
</tr>
</tbody>
</table>

Built by Haimson Research
Electron Beam Expansion-Analytic

- Beam envelope equation at waist diameter \((2r_m)\) for space charge and emittance to calculate expansion

\[
r_{m''} - \frac{\varepsilon_n^2}{\beta^2\gamma^2 r_m^3} - \frac{K}{r_m} = 0
\]

space charge term

emittance term

- Perveance

\[
K \equiv \frac{qI}{2\pi\varepsilon_0 m\beta^3\gamma^3 c^3}
\]

For 80 A, 500 kV

\[
K = 0.0018
\]

- Emittance

\[
\tilde{\varepsilon}_n = \beta\gamma\varepsilon = \text{const.}
\]

Liouville Thm: non-interacting particles

\[
\varepsilon_n = 4\tilde{\varepsilon}_n = 2a \left(\frac{k_B T}{mc^2}\right)^{1/2}
\]

Effective normalized emittance

At cathode \(a \approx 2.5\, cm\), \(T \approx 1000\, ^{\circ}C\)

\[
\varepsilon_n = 23\text{mm} \cdot \text{mrad}
\]
Comparing space charge to emittance term at waist ($r_m = 3.75$ mm)

$$\frac{Emit.}{S.C.} = \frac{\epsilon_n^2}{K\beta^2\gamma^2 r_m^2} = 0.007$$

Proved space charge dominates beam expansion post-gun
- vs. K. Nichols last month (emittance dominated)

Use code MICHELLE (SAIC) and compare to numerically integrated waist
Electron beam electrostatically focused to waist diameter of 7.5 mm at z=0

- Variable e-beam size with lens

- Magnetic lens on sliders
  - Adjust current (magnetic field) through lens to refocus
Michelle: Magnetic Lens Example

- Adjust lens location (on sliders) to change beam size
- Adjust coil current to change focusing
- For lens at 220 mm

\[ \int_{z_1}^{z_2} B^2 dz = 1.56 \times 10^6 \text{ Gauss}^2 \text{ cm} \]

Location of waist (z=0)

Michelle Particle Trajectories

Michelle Beam Profile

Mag. Lens Profile

Location of waist
Magnetic Lens

- Magnetic lens slides along z axis, set lens field to appropriate strength
- Thin lens, with space charge EOM
  \[ r_m'' - \frac{K}{r_m} + \alpha^2 r_m = 0 \]
  \[ \alpha^2 = \left(\frac{qB}{2mc\gamma\beta}\right)^2 \]
- E-beam radius \(3.5 \leq r_m \leq 20\) mm

Appropriate B field to straighten beam

\[ \int_{z_1}^{z_2} B^2 dz \quad (\text{Gauss}^2\text{-cm}) \]
MTM Design: CSRR

- Based on modified CSRR design-electric analogy to SRR
- CSRR already shown to have negative group velocity waves
  - Negative $\varepsilon$: property of CSRR
  - Negative $\mu$: under TM fundamental cutoff

Shapiro, Phys. Rev. B 2012
QuadMTM

- Negative index: Transverse confinement, CSRR
- Simple design: planar, use of standard components coupling between fast and MTM wave

QuadMTM design, f~2.5 GHz

Cut CSRR in WG

Period l=7 mm

CSRR Surface

Electron Beam

72 mm
QuadMTM Dispersion Relation

- HFSS
  - Simulate eigenmodes of 1/8th cut (symmetry)
  - Gives field profile and Dispersion Relation

\[ k_z L = \phi \]

Beam line dispersion relation:

\[ 2\pi f - \beta_e v_{beam} = 0 \]
TM-Hybrid Mode

\[ \phi = 25 \, \text{deg} \]

\[ \phi = 0 \, \text{deg} \]
In/Out Coupling Structure

- **Interaction Circuit**
  - TM-Hybrid cutoff frequency in cavity separated from fast TE modes in waveguides

- **Coupler Circuit**
  - Expand rectangular waveguide to couple in/out
  - Exploit coupling between fast TE mode in waveguides

- Higher frequency fast TE mode
- Fast wave cutoff ~Hybrid TM cutoff
QuadMTM Coupling

- Expand waveguide
  - Get conversion between fast and hybrid mode
Preliminary investigation of fast-slow wave conversion in coupled to non-coupled section

Fast Wave Launched in waveguide with port

Mostly hybrid mode in interaction circuit

Mode Conversion
Other Geometries

- Other geometries considered
  - Square, hexagonal, triangular, octagonal
For a rough estimation of beam coupling use TWT theory

The coupling impedance is given by

\[ Z = \frac{|E_w|^2}{2\beta_0^2 P} \]

\[ P = \frac{1}{2} Re \int (\vec{E} \times \vec{H}^*) \cdot d\vec{A} \]

\[ E_w = \frac{1}{l} \int E_z(z)e^{i\beta_e z} dz \]

Synchronism so that \( \beta_e \approx \beta_0 = \frac{\phi}{l} \quad (\beta_e = \frac{v_{beam}}{2\pi f}) \)

P small, integrated over entire circuit area (whole TM-Hybrid mode)
For the TM-hybrid mode

\[ Z_{TM} = 37 \text{ Ohm} \]

Define Pierce parameter-for 500 kV, 80 A; \( \phi = 25 \text{ deg} \)

\[ C = \left( \frac{IZ}{4V} \right)^{1/3} = 0.12 \]
Linear Gain Regime

- TWT similarity-3 waves: decaying, growing, constant-for sufficient length growing wave is dominant

- Gain of growing wave
  \[ G(\text{dB}) = -9.54 + 7.53 \times CL\beta_0 \]
  
  L is the length of the device, \( \beta_0 = 64.8 \text{ m}^{-1} \)

  \[ Gain = 47 \text{ dB/m} \]

- Assumes: small space charge, synchronism, linear regime, no loss
Breakdown Power

- Simple estimate from HFSS eigenmode simulation - take peak field and power flux

\[ P = \frac{1}{2} Re \int (\vec{E} \times \vec{H}^*) \cdot d\vec{A} \]

\[ = 1.8 \times 10^{-9} \text{ W} \]

\[ E_{\text{peak}} = 0.6 \text{ V/m} \]

- If breakdown field in device is 90 MV/m

\[ P_{\text{breakdown}} = \left( \frac{90 \times 10^6}{0.6} \right)^2 1.8 \times 10^{-9} \]

\[ P_{\text{breakdown}} = 40 \text{ MW} \]

- \( P_{\text{beam}} = 40 \text{ MW} \), so we don’t expect breakdown

- Could reduce fields by rounding edges, optimizing MTM parameters
Future Work

- **Optimize Design**
  - Optimize MTM parameters for device
  - Include loss in dispersion relation
  - Implement CST Particle Studio (beam-wave interaction)
    - PIC solver
    - Wakefield solver
  - Consider nonlinear TWT gain equation
    - Use code Latte
    - Write nonlinear bunching code

- **Initiate Experiments**
  - Build structure
  - Cold test structure
  - Install structure at MIT
Conclusions

- Electron Beam Physics: simulated electron beam with Michelle
  - Agrees with analytical theory
  - Showed space charge dominates

- MTM: QuadMTM structure
  - Hybrid TM mode for beam interaction
  - Negative dispersion

- Microwave Engineering/Design
  - Investigated coupling of power in/out of structure

- Beam-Wave Interaction
  - Estimated coupling to beam with analytical linear theory

- Experiment Design
Acknowledgements

- **MURI collaborators**
  - LSU
  - UNM
  - Ohio State
  - UC-Irvine

- **MIT WAB–staff**
  - Rick Temkin
  - Ivan Mastovsky
  - Michael Shapiro
  - Bill Guss
  - Paul Woskov

- **MIT WAB-postdocs**
  - Sudheer Jawla

- **MIT WAB-grad students and postdocs**
  - Sergey Arsenyev
  - Elizabeth Kowalski
  - Xueying Lu
  - Brian Munroe
  - Emilio Nanni*
  - Alexander Soane
  - Sam Schaub
  - David Tax
  - JieXi Zhang

- **MIT WAB-undergrads**
  - Samantha Lewis

- **Visiting Scientists**
  - Zhaoyun Duan

*Now Graduated*