NEW OPPORTUNITIES IN VACUUM ELECTRONICS USING PHOTONIC BAND GAP STRUCTURES

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OUTLINE

- Motivation
- Photonic Band Gap Structures as mode selective circuits
- Theory of PBG structures
- MIT experiments based on PBG structures
  - 17 GHz accelerating structure
  - 140 GHz overmoded gyrotron
- Additional applications of PBG structures
- Summary
MOTIVATION

“Overmoded” yet “mode-selective” interaction structures can pave the way for building millimeter/sub-millimeter wave microwave sources.

- At millimeter/sub-millimeter wave frequencies fundamental mode interaction circuits are too small to handle high peak or average power.
- Overmoded operation permits larger dimension resonators but mode competition presents a big problem.
- PBG structures offer a lot of promise for building mode selective interaction structures.
Overmoded resonators are necessary for high frequency gyrotrons but they suffer from mode-competition which reduces the efficiency and stability of the design mode.
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PBG STRUCTURES

- Oversized structure
  - Ease of fabrication
  - Suitable for high frequency (> 100 GHz)
- Reduced mode population
  - Periodic boundary discriminates modes with different frequencies
  - Inhomogeneous boundary reduces the number of modes
- Simple coupling scheme
- Graceful degradation
- Possible applications
  - input / output couplers for klystrons, gyro-klystrons
  - interaction circuits for TWT, gyro-TWT, gyro-twystron

A 140 GHz, TE_{041}-like mode PBG cavity for an overmoded gyrotron oscillator experiment

Disassembled view of a 17 GHz TM_{010} like PBG cavity for potential application in linear accelerators
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A **photonic band gap (PBG) structure** is a one-, two- or three-dimensional periodic metallic and/or dielectric system (e.g., of metal rods).

**Applications:** Use of PBG structures, and in particular 2D PBG structures, is a promising approach to realization of mode selective circuits.
PBG STRUCTURES

Square lattice

Reciprocal lattice
(irreducible Brillouin zone is shaded)

TM Modes

TE Modes

\( \Gamma \) X M \( \Gamma \)

\( a/b = 0.2 \)

<table>
<thead>
<tr>
<th>Frequency (( \phi b/c ))</th>
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<tbody>
<tr>
<td>12.0</td>
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<tr>
<td>8.0</td>
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<tr>
<td>4.0</td>
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\( a/b = 0.2 \)
PBG STRUCTURES

Triangular lattice

Reciprocal lattice (irreducible Brillouin zone is shaded)

TM Modes

TE Modes

a/b = 0.2
TM gap variation with filling fraction. The dot represents the operating point of the 17 GHz TM$_{010}$ accelerator cavity show below.

TE gap variation with filling fraction. The dot represents the operating point of the 140 GHz TE$_{041}$ gyrotron cavity show below.
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PBG ACCELERATING CELL

17 GHZ ACCELERATING CELL
PBG ACCELERATING CELL

- TM$_{010}$-like operating mode
- Formed by 2D triangular lattice of metal rods with defect in center
- Oversized structure
- Suppression of higher order modes and wakefields
- Shunt impedance comparable to that of a pillbox structure
- Measured Ohmic Q = 600

The 17 GHz TM$_{010}$-like mode cell for accelerator applications

HFSS simulations showing the electric field contours of the TM$_{010}$-like mode
COUPLING INTO PBG CELL

$S_{11}$ measurement (cold test) and HFSS simulation

Calculated total Q = 250, Ohmic Q = 500

- 6 rods completely removed,
- 2 rods partially withdrawn
- Measured total Q = 300
- Ohmic Q = 600
## PULSE HEATING & WAKEFIELDS

<table>
<thead>
<tr>
<th></th>
<th>PBG Cavity</th>
<th>Pillbox Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eigenfrequency (GHz)</strong></td>
<td>17.3</td>
<td>17.3</td>
</tr>
<tr>
<td><strong>Pulse heating ΔT (deg. C) for 1MW, 100ns pulse</strong></td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td><strong>Max. longitudinal wake potential (V/pC per cell)</strong></td>
<td>8.6</td>
<td>16</td>
</tr>
<tr>
<td><strong>Max. transverse dipole mode wake potential (V/pC per cell)</strong></td>
<td>2.7</td>
<td>56</td>
</tr>
</tbody>
</table>

- Longitudinal wake potential of PBG accelerator structure is smaller by factor of 2
- Transverse wake potential (dipole modes) of PBG structure is smaller by factor of 20
- HFSS simulations indicate no HOM in PBG cavity
HPM APPLICATIONS

- Previous research in on application of PBG structures in accelerators

- Microwave generation is a potential application

- Accelerator structure design is very similar to klystron or TWT design

- Advantages of PBG interaction structure
  - Oversized structure
  - Harmonic suppression
  - Simple input/output coupling
  - Simple fabrication
PBG GYROTRON

140 GHZ GYROTRON
Design a lattice with a band gap around the desired operating frequency

Create a defect (remove rods) in the lattice so as to create a defect mode which will serve as the operating mode of the structure

The operating mode being in the bandgap is confined in the transverse direction

Competing modes which are offset in frequency will not be confined if they lie in the lattice passband
140 GHz PBG RESONATOR

Cross section of the PBG cavity with a TE$_{04}$ like operating mode at 139.8 GHz

Cross-section of a conventional cylindrical cavity with a TE$_{04}$ operating mode at 139.8 GHz

<table>
<thead>
<tr>
<th>Frequency</th>
<th>139.8 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>TE$_{041}$ like</td>
</tr>
<tr>
<td>Cavity length</td>
<td>8 $\lambda$</td>
</tr>
<tr>
<td>Ohmic Q (HFSS Sim.)</td>
<td>$\sim$ 13000</td>
</tr>
</tbody>
</table>
GYROTRON TEST STAND

- 100 kV, 70 A, 3μs capable Modulator
- 6.5 Tesla Superconducting Magnet
- Magnetron Injection Gun 75 kV, 7 A
- Demountable setup for quick change of experiments
140 GHz PHOTONIC BAND GAP GYROTRON
PBG GYROTRON RESULTS

- Unprecedented range of single mode operation
- 25 kW peak power at 140.04 GHz
- Efficiency limited by high diffraction Q

Frequency = 140.04 GHz
Voltage = 67.52 kV
Current = 5.10 A

Power (kW) vs. Magnetic Field (Tesla) graph

RF 2001 Workshop, 1-5 October 2001
PBG GYROKLYSTRON

140 GHZ PBG GYROKLYSTRON

- TE_{041}-like eigenmode at 139.33 GHz
- Q ~ 855
- Hybrid (metal-dielectric) PBG structure
- Dielectric loading along the length of the resonator

\[ \varepsilon = 12.26, \tan \delta = 0.3 \]

- TE_{041}-like eigenmode at 139.5 GHz
- Q ~ 176
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FUTURE RESEARCH

- PBG structures show potential for moderate average power (100’s of CW) and high peak power (10’s of kW) applications at high frequency (W-band and above)

- Experimental investigation of ohmic losses
  - Inner row of rods can be cooled by a water channel through each rod
  - Conduction cooling through the end plates

- Transverse energy extraction for lowering the diffractive Q in gyrotron/gyroklystron resonators
  - Transverse coupling into the 17 GHz PBG accelerating cell
  - Very attractive for sub-millimeter wave gyrotrons which need longer resonators (L ~ 20λ) for high efficiency
FUTURE RESEARCH

- Experimental investigation of low Q hybrid (metal+dielectric) PBG structures for klystron/gyroklystron applications
- A PBG Gyro-TWT interaction circuit can be designed to completely suppress the backward wave oscillation
- W-band overmoded conventional klystron/TWT with 100 W cw power
- HPM generation in a PBG interaction structure
SUMMARY

- Gyrotron with a PBG resonator designed, built, and tested
  - 25 kW power at 140 GHz
  - Unprecedented range of single mode operation
  - Spurious modes at least 22 dB below the operating mode

- Cold tests of a PBG accelerating cell at 17 GHz
  - Input coupling
  - Higher order mode suppression
  - Concept is equally applicable to HPM

- Future applications of PBG structures in both fast wave and slow wave microwave tubes and accelerator applications
REFERENCES
