Degenerate band edge oscillator (DBEO)

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Collaboration with

Edl Schamiloğlu, Christos Christodoulou
S. Yurt, X. Pan, Y. Atmatzakis

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Outline and Summary

- Degenerate band edge (DBE) in slow-wave structures
- Progress in cold test study of DBE in metallic waveguide (collaboration with UNM*)
- Low starting current calculations for DBE oscillators (DBEO)
- All metallic slow-wave structures (SWSs) with DBE
- Preliminary PIC calculations for the interaction between an SWS with DBE and electron beam (collaboration with UNM**)
- Conclusion

* Collaboration with X. Pan, G. Atmatzakis and Prof. C. Christodoulou, ECE Department, University of New Mexico
** Collaboration with S. Yurt, and Prof. E. Schamiloglu, ECE Department, University of New Mexico


Degenerate band edge (DBE)

Waveguide structures can support a DBE, instead of only an RBE (regular band edge). At DBE, we have four degenerate modes

\[
(\omega_d - \omega) \propto (k - k_d)^4
\]

Bloch wavenumber \( k_d = \pi / d \)


Four mode synchronization

Dispersion relation for SWS with DBE and e-beam

\[
\left( \omega_d - \omega \right) - h(k - k_d)^4 \left[ \omega - u_0k \right]^2 = C(\omega, k, I_0)
\]

Four EM modes

e-beam

coupling

Four mode super synchronization

\[
u_0 \approx \frac{\omega_d}{k_d}
\]

\(u_0\): electron's average velocity


Slow wave structures with DBE

DBE Frequency 2.1 GHz

\[ \varphi_{\text{DBE}} \sim 68^\circ \]

Dispersion diagram

Full-wave simulations (CST Microwave Studio)

Group delay

Waveguide fabrication and cold test

Copper rings + Foam support for rings + Waveguide flanges

Copper rings  
Foam support for rings  
Waveguide flanges

S-parameters measurement done using KEYSIGHT N5247A PNA-X Microwave Network Analyzer

Different lengths of SWS

Measurements:

1- Reflection and transmission parameters  
2- Group delay  
3- Dispersion relation

Collaboration with UNM, Christos Christodoulou, X. Pan, Y. Atmatzakis, UNM
Cold test: 1 port, S-parameters

Different lengths

<table>
<thead>
<tr>
<th>$S_{11}$</th>
<th>(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N = 2$</td>
<td></td>
</tr>
<tr>
<td>$N = 4$</td>
<td></td>
</tr>
<tr>
<td>$N = 8$</td>
<td></td>
</tr>
</tbody>
</table>

$N$ is number of unit cells

DBE resonance peak

- Only measuring $S_{11}$ (the end of the waveguide is shorted)
- $|S_{11}| < 0$ dB means coupling to losses in the waveguide
Cold test: resonances

9 resonances are extracted from measurements for the 8 cell resonator

- Resonance frequencies are used to synthesize the dispersion relation of the periodic waveguide

Number of resonances = $N + 1$, $N =$ number of cells

Different lengths

$|S_{11}|$ (dB)

Frequency (GHz)

1 port measurement

Short circuit
Measurement of dispersion relation

- Good agreement between full-wave simulations (CST) and measurements
- Other measurements (quality factor, delay, etc) have been also carried out, confirming the existence of DBE

Coupled Transmission Lines (CTL) formalism

- At DBE, four degenerate modes interact (synchronized) with the electron beam
- The interactive system can be modeled using generalized Pierce theory [1–3]. DBE is associated with giant gain and low-start current

Recently published papers:


Degenerate band edge oscillator (DBEO)

- The starting oscillation current $I_{st}$ decreases with increasing DBEO length.
Degenerate band edge oscillator (DBEO)

- The starting oscillation current $I_{st}$ decreases with increasing DBEO length.

- Scales as

$$I_{st} = \frac{\alpha}{N^5}, \quad N : \text{number of unit cells}$$
Degenerate band edge oscillator (DBEO)

- The starting oscillation current $I_{st}$ decreases with increasing DBEO length.

- Scales as

$$I_{st} = \frac{\alpha}{N^5}, \quad N: \text{number of unit cells}$$

- Compared to the conventional BWO, DBEO has lower starting current and better scaling

$$I_{st} (\text{BWO}) \propto \frac{1}{N^3}, \quad N: \text{number of unit cells}$$

All-metallic SWS with DBE for high power

SWS 1: Periodic “corrugated” waveguide with elliptical cross sections

- A unit cell consisting of circular waveguide loaded with two irises of elliptical shape
- Elliptical irises are misaligned with angle $\phi$
- Similar to corrugated waveguides, except the corrugation’s cross-sections are elliptic

Circular waveguide

Elliptical cross-section

Dispersion diagram

Cross-section

Period $d$

Side view

Normalised Bloch Wavenumber $k d / \pi$

Frequency (GHz)

500 kV beam line DBE
**SWS 2: Periodic waveguide with split-ring loading**

- A unit cell consisting of circular waveguide loaded with two coupled split-rings
- Circular or elliptical split-rings
- Split-rings are connected to the waveguide wall

**Dispersion diagram**

Host waveguide operates below cutoff
DBE frequency ~ 1.2 GHz
SWS 3: Rectangular waveguide loaded with coupled CSRR metasurfaces

- A unit cell consisting of rectangular waveguide loaded with two metasurfaces
- Two coupled metasurfaces are implemented with Complimentary Split Ring Resonators (CSRR)
- There is asymmetry between the two metasurfaces (shape+longitudinal offset)

Rectangular waveguide

CSRR metasurface 1

CSRR metasurface 2

Unit cell

Period $d$

Period $d$

Cut off waveguide

Dispersion diagram

SBE: Split band edge

Group velocity = 0

Can be readily optimized to exhibit a DBE as well

Corrugated SWS, elliptical cross sections

The structure is designed to exhibit a DBE for the following parameters

<table>
<thead>
<tr>
<th>$r_{wg}$</th>
<th>$d$</th>
<th>$h_1$</th>
<th>$h_2$</th>
<th>$a$</th>
<th>$b$</th>
<th>$\varphi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>33 mm</td>
<td>30 mm</td>
<td>15 mm</td>
<td>3 mm</td>
<td>33 mm</td>
<td>18 mm</td>
<td>45 deg.</td>
</tr>
</tbody>
</table>

DBE frequency $\sim$ 4.5 GHz

- Elliptical cross sections support two polarizations
- Modes are coupled periodically
- DBE, and other degeneracy conditions can be achieved

Yellow: metal

$r_{wg}$: circular waveguide radius, $d$: period, $a$: elliptical iris major radius, $b$: elliptical iris minor radius, $\varphi$: misalignment angle, $h$: iris thickness, $s$: separation between irises
Corrugated SWS, elliptical cross sections

Dispersion relation

The DBE mode is designed to have a higher interaction impedance than the lower order mode.

Electric field $E_z$ component distribution of DBE mode

Strong $E_z$ component on the waveguide axis
Preliminary PIC simulations: MAGIC 3D

Simulation Parameters

<table>
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<tr>
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<th>Value</th>
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<tr>
<td>Cathode Radius</td>
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<td>3 cm</td>
</tr>
<tr>
<td>Applied Voltage</td>
<td>500 kV</td>
</tr>
<tr>
<td>Voltage Rise-Time</td>
<td>2 ns</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>3 T</td>
</tr>
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Collaboration with UNM, Edl Schamiloglu, S. Yurt
Case 1: Constant beam voltage

- **Beam voltage**
  - Initial voltage: ~500 kV
  - Voltage remains relatively constant.

- **Beam current**
  - Current: ~0 kA
  - Current remains relatively constant.

- **Output microwave power**
  - Peak power: 95 MW
  - Power fluctuates over time.

- **Input beam power**
  - ~1 GW

- **Efficiency**
  - ~9.5%

- **Fast rise time**
  - ~8 ns

Collaboration with UNM, Edl Schamiloglu, S. Yurt
Case 2: 12 ns beam pulse (UNM’s SINUS-6)

- Fast starting of oscillation
- Will be optimized for power extraction and suppression of higher order modes (this is a first demonstration, it has not been optimized for high power. We have a scheme to do it.)

At DBE frequency:
- ~ 4.5 GHz

Output spectrum

Collaboration with UNM, Edl Schamiloglu, S. Yurt
Conclusions

- Cold experimental test was performed to demonstrate for the first time DBE in all metallic slow-wave structures

- Degenerate band edge oscillator was shown to have a lower starting current with better scaling than conventional backward wave oscillator

- We have shown that DBE can be obtained in various metallic loaded waveguides including metamaterial-based SWSs (based on MIT design)

- Preliminary PIC simulations demonstrated fast rise time for the DBEO

Future work

- Optimize potential DBE structures using PIC codes (MAGIC + CST Particle Studio) for high power applications

- Optimize power extraction to improve efficiency (for low beam current)

- Investigate gain/loss balance scheme to maintain the DBE with high power beam in a pulse-compression-based operation (with beam as switch)
Thank you
Auxiliary slides
Corrugated SWS, elliptical cross sections

Field maps of the DBE mode

Distribution of $E_z$

$\max(E_z)$ on axis

Interaction impedance (normalized)
\[ V_{out} = - \int E \cdot dl \]

**Integration line over the output port**

**Simulation Parameters**

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Windowed Fourier transform of output voltage

Time domain output signal

FFT Using Rectangular window

Spectrum of output signal

Voltage Spectrum [KV/GHz]
Windowed Fourier transform

Voltage Spectrum [KV/GHz]

7 - 10 ns
Windowed Fourier transform

Voltage Spectrum [KV/GHz]
Windowed Fourier transform

Voltage Spectrum  [KV/GHz]

20 – 40 ns
Windowed Fourier transform

40 – 60 ns
Windowed Fourier transform

Voltage Spectrum [KV/GHz]
Windowed Fourier transform

Voltage Spectrum [KV/GHz]

80 – 95 ns
Windowed Fourier transform

Voltage Spectrum [KV/GHz]

100 – 105 ns
Conclusions:

- Oscillation with DBE frequency starts faster than other modes.
- DBE has a fast rise time thanks to the large beam current.