FERROELECTRIC BASED HIGH POWER COMPONENTS FOR L-BAND ACCELERATOR APPLICATIONS

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On behalf of Euclid Techlabs/BNL/FNAL collaboration
Euclid Techlabs LLC

Euclid TechLabs LLC, founded in 1999 is a company specializing in the development of new dielectric materials and advanced designs for high power/high frequency applications. Additional areas of expertise include dielectric structure based accelerators and "smart" materials technology and applications.

- 2014: 12 people research staff and 3 administrative,
- 2 offices: Bolingbrook, IL (lab) and Gaithersburg MD (administrative).
- Tight collaborations with National Labs: Fermi, Argonne, BNL, Berkely.
- Joined Fermi/IARC lately.
Products and Projects

Photoinjectors:
- L-band high peak current AWA-style
- S-band (LCLS-style)

UHV L-band RF window

Linear and non-linear ceramics
low loss; various form factors

BPM compact readout

Compact, detachable coaxial coupler for SRF cavity
(joint project with FNAL)
Research on dielectric loaded accelerating structures (DLA)

Experiments with DLA were done by Euclid Techlabs at: Argonne, Naval Research Laboratory, Brookhaven, SLAC

• designs: 7-26 GHz
• scalable to THz

S. Antipov, et. al, RSI 84 (2) (2013)
C. Jing, et. al, PRSTAB, v14(2) (2011)
Experimental Demonstration of Wakefield Acceleration in a Tunable Dielectric Loaded Accelerating Structure

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We report on a collinear wakefield experiment using the first tunable dielectric loaded accelerating structure. By introducing an extra layer of nonlinear ferroelectric, which has a dielectric constant sensitive to temperature and dc bias, the frequency of a dielectric loaded accelerating structure can be tuned. During the experiment, we observed a significant wakefield acceleration of electrons in a multilayer structure, with the frequency of the accelerating structure being tunable by changing the bias on the ferroelectric layer.

ε(E) for ferroelectric dielectric composite

NONLINEAR CERAMIC
Ferroelectric Based Tuner (ultrafast phase shifter) for SRF Accelerator Operation
A fast controllable phase shifter would allow microphonics compensation for CW SRF accelerators supporting ERLs and FEL.

Nonlinear ferroelectric microwave components can control the tuning or the input power coupling for rf cavities. Applying a bias voltage across a nonlinear ferroelectric changes its permittivity. This effect can be used to cause a phase change of a propagating rf signal or change the resonant frequency of a cavity. The key is the development of a low loss highly tunable ferroelectric material.

Topic was suggested by BNL (Ilan Ben-Zvi)
For a typical ferroelectric tuner needed for ERL SC cavity excitation, on need ferroelectric material having the tunability of 0.06 and loss tangent of \( \sim 0.001 \) in order to get the power gain of 12-15.

\[
P_g = P_{loss} + \omega W / Q_0 \quad \Delta \omega = 2Q_0 / \omega. \quad P_{g,\text{max}} = W \delta \omega
\]

\[
P_g / P_{g,\text{max}} = \delta \omega / \Delta \omega \left( 1 - 4tn\delta \frac{\eta(\phi_0)e}{\Delta e} \right).
\]

For BNL ERL and the tuner described in the Euclid Proposal (\( \Delta e/e=0.2 \) and \( \phi_0=135^\circ \))
Progress on BST Material Development

(Ba, Sr)TiO$_4$+Mg oxides

BST(M), $\varepsilon \sim 50-150$

record low values of dielectric constant and loss tangent at relatively high tunability level required for high power bulk tuner operating in air (< 30 kV/cm) and in vacuum (up to 80 kV/cm).
### Ferroelectric ceramic properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dielectric constant, $\varepsilon$</td>
<td>50-450</td>
</tr>
<tr>
<td>tunability, $\Delta\varepsilon$</td>
<td>$&gt;30@15\text{kV}\cdot\text{cm}^{-1}$ of the bias field</td>
</tr>
<tr>
<td>response time</td>
<td>&lt; 10 ns</td>
</tr>
<tr>
<td>loss tangent at 1.3 GHz, tan$\delta$</td>
<td>$\sim 1\times 10^{-3}$</td>
</tr>
<tr>
<td>breakdown limit</td>
<td>200 kV/cm</td>
</tr>
<tr>
<td>thermal conductivity, $K$</td>
<td>7.02 W/m$\cdot$K</td>
</tr>
<tr>
<td>specific heat, $C$</td>
<td>0.605 kJ/kg$\cdot$K</td>
</tr>
<tr>
<td>density, $\rho$</td>
<td>4.86 g/cm$^3$</td>
</tr>
<tr>
<td>coefficient of thermal expansion</td>
<td>$10.1\times 10^{-6}$ K$^{-1}$</td>
</tr>
<tr>
<td>temperature tolerance, $\partial\varepsilon/\partial T$</td>
<td>(1-3) K$^{-1}$</td>
</tr>
</tbody>
</table>
Issues with the ferroelectric elements

- **Dielectric constant** has to be low (~ 100)
- **Loss factor** has to be low ~ $1.0 \times 10^{-4}$ at 1 GHz
- **Tuning range** has to be high ~ 6-8% at 20kV/cm
- **Residual effects** have to be mitigated

(Ba, Sr)TiO$_4$+Mg oxides
Frequency dependence of $\varepsilon$ and $\tan \delta$ for the ferroelectrics with low permittivity
Ferroelectric composite materials

Patent US 8,067,324 B2, Nov. 29, 2011

Powders

Ceramics

SEM image of the initial powders of barium titanate (a) and strontium titanate (b).

SEM images and EDS data of the sample on the basis of BST ferroelectric with linear Mg-containing additive (T = 1420 °C) (a, b) and (T = 1400 °C) (c).

SEM image of the boundary interface region in between the grains of the BST-MgO-Mg₂TiO₄ composite material.

Static and dynamic tunability as a function of the permittivity.
Euclid has developed a sputtering system for depositing of a variety of metallization and dielectric deposition applications.
BST Based Tuner Design (assembly)
BST Based Tuner Design (parts)
Tube Characterization
Material Characterization Results (I)

<table>
<thead>
<tr>
<th>Tube</th>
<th>ID(mm)</th>
<th>OD(mm)</th>
<th>L(mm)</th>
<th>T(°C)</th>
<th>$f_{TE01}$(MHz)</th>
<th>Eps</th>
<th>Eps (22.1°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.42-16.64</td>
<td>37.6-38.3</td>
<td>45.82</td>
<td>22.1</td>
<td>767.475</td>
<td>149.2</td>
<td>149.2</td>
</tr>
<tr>
<td>1</td>
<td>15.9-16.46</td>
<td>36.7-37.85</td>
<td>46</td>
<td>23.5</td>
<td>743.88</td>
<td>159.1</td>
<td>160.6</td>
</tr>
<tr>
<td>2</td>
<td>16.02-16.44</td>
<td>37-37.87</td>
<td>45.82</td>
<td>24.3</td>
<td>744.94</td>
<td>158.5</td>
<td>160.7</td>
</tr>
<tr>
<td>3</td>
<td>16-16.4</td>
<td>36.83-37.79</td>
<td>46.16</td>
<td>24</td>
<td>744.76</td>
<td>158.6</td>
<td>160.6</td>
</tr>
<tr>
<td>4</td>
<td>16.02-16.47</td>
<td>36.91-37.8</td>
<td>45.81</td>
<td>24.4</td>
<td>746.3825</td>
<td>158.2</td>
<td>160.6</td>
</tr>
<tr>
<td>5</td>
<td>15.93-16.4</td>
<td>36.81-37.65</td>
<td>45.95</td>
<td>25.3</td>
<td>750.3575</td>
<td>156.5</td>
<td>159.9</td>
</tr>
<tr>
<td>6</td>
<td>15.93-16.35</td>
<td>36.94-37.7</td>
<td>47.93</td>
<td>25.8</td>
<td>750.175</td>
<td>155.2</td>
<td>159.1</td>
</tr>
</tbody>
</table>

Tube#4: Eps(@39.6°C)=138.1; Loss tan (@ 39.6°C) ~ 8E-4
Material Characterization Results (II)

Testing of the BST (M) at 400°C with 3 different metallizations (1) Al (1um)+Au (5 um), (2) Cr (50нм)+Cu (1um)+Au (5um) and (3) Au (1um+5um)
Time response measurements
Time response measurements after annealing at oxygen atmosphere
Tasks

- **Task 1:** Design simulation studies for the ferroelectric phase shifter design.
- **Task 2:** Development of a ferroelectric material having a dielectric constant in the range 80-150, tunability 5-6% at 15-20 kV/cm and Qxf ~ 1500-1700.
- **Task 3:** Final design optimization of the tuning elements to further minimize losses and to improve efficiency. A HV connector design.
- **Task 4:** Engineering design for the phase shifter.
- **Task 5:** Phase shifter is under manufacture and assembled.
- **Task 6:** Low power tests of the ferroelectric phase shifter under high dc bias control voltages.
- **Task 7:** High-power tests and evaluation of the ferroelectric phase shifter will be carried out to study the device characteristics as functions of rf power level, HV bias level, temperature control and bandwidth.
The ultimate goal of the Phase II project regarding BST based composition development is designing a ferroelectric element based on BST(M) material with permittivity reduced to 80-150, tunability \( \Delta \varepsilon / \varepsilon \) of 1.05 -1.06 at 15-20 kV/cm bias field magnitude, and loss tangent 5-6\( \times 10^{-4} \) at 700 MHz. Currently have been demonstrated:

- Dielectric constant ~ 100-150
- Loss factor ~ 1.0 \( \times 10^{-4} \) at 1 GHz
- Tuning ~ 6% at 20kV/cm
- Residual effects can be mitigated with metallization technology

Ferroelectric components have been fabricated; the tuner assembling, cold and high power testing is ongoing.