FAST FERROELECTRIC PHASE SHIFTER DESIGN FOR ERLs *

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- in ERLs, the beam loading is small and power requirements are determined by:
  - ohmic losses in walls,
  - imbalance between beam currents
  - cavity’s resonant frequency changes due to mech. vibrations (microphonics)

- all above may require a change in coupling (cavity-feedline)
- bandwidth of the cavity, which typically is narrow, will grow...
- extra power is needed

- fight these effects using an internal piezoelectric mechanical tuner
- active rapid tuners to apply a corrective phase shift to the reflected wave, which can be reintroduced to the cavity and hence reduce the required power.
SRF cavity phase and amplitude control using an external tuner in a magic-T configuration with adjustable phase shifters.
Configuration with a resonance ring
- ERLs have stringent requirements on amplitude and phase stability:
  - amplitude stability $\sim 3 \cdot 10^{-4}$ (Cornell’s ERL)
  - phase stability $\sim 0.06$ degree

- The aforesaid means having a bandwidth $\sim 1$ MHz ($\sim$1 μsec)

- High power fast ferrite tuners … have response time $\sim 30$ μsec
  - main reason is eddy currents
  - high power consumption for bias
  - high price ($\sim$80,000 per unit)

- High power fast ferroelectric tuner … may offer a solution

- Proposed ferroelectric tuners are based on BST-ceramic ($\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$) with
  - $\varepsilon \approx 500$
  - response time (intrinsic) $\sim 10$ ns
  - loss tangent $\sim 1.5 \cdot 10^{-3}$ (at $\sim$1GHz)
  - electric breakdown strength 100-200 kV/cm
  - pulsed DC bias of $\sim$20-50 kV/cm changes $\varepsilon$ by $\sim$25%
Properties of BST ceramic, which is proposed as an active medium for ferroelectric based tuners/phase shifters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dielectric constant, $\varepsilon$</td>
<td>$\sim 500$</td>
</tr>
<tr>
<td>tunability, $\partial \varepsilon / \partial E_{bias}$ ($E_{bias}$ is the bias field)</td>
<td>$&gt; 2/(\text{kV/cm})$</td>
</tr>
<tr>
<td>response time</td>
<td>$&lt; 10$ ns</td>
</tr>
<tr>
<td>loss tangent at 1.3 GHz, $tg(\delta)$ (meas. by Omega-P)</td>
<td>$\sim 1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>breakdown limit</td>
<td>200 kV/cm</td>
</tr>
<tr>
<td>thermal conductivity, $K$</td>
<td>7.02 W/m·ºK</td>
</tr>
<tr>
<td>specific heat, $C$</td>
<td>0.605 kJ/kg·ºK</td>
</tr>
<tr>
<td>density, $\rho$</td>
<td>4.86 g/cm³</td>
</tr>
<tr>
<td>coefficient of thermal expansion</td>
<td>$10.1 \times 10^{-6}$ /ºK</td>
</tr>
<tr>
<td>temperature tolerance, $\partial \varepsilon / \partial T$</td>
<td>3 /ºK</td>
</tr>
</tbody>
</table>
Examples of ferroelectric material: rings, bars by Euclid Tech-Labs LLC

diameter = 106 mm; thickness = 2.8 mm; length = 22 mm

diameter = 106 mm; thickness = 12 mm; length = 22 mm

width = 6 mm; height = 5 mm; length = ~108 mm
Measurements of loss of ferroelectric ceramic:

\[ \text{f} \sim 830 \text{ MHz, } Q \sim 900, \tan(\sigma) \sim 1.1 \cdot 10^{-3} \]

\[ \text{f} \sim 1396 \text{ MHz, } Q \sim 1620, \tan(\sigma) \sim 2 \cdot 10^{-3} \]

The ceramic for L-band is a “quick” modification of that for X-band, consequently:

- The losses are on “high side”
- Efforts are underway to re-design the ceramic to reduce losses in L-band
Measurements of tunability of ferroelectric at high voltages:

The ceramic for L-band is a “quick” modification of that for X-band, consequently:

- The initial portion of the curve indicates poor sensitivity to the applied voltage of low values.
- Efforts are underway to re-design the ceramic to make the initial portion of curve to be close to a linear dependence.
Designs for ferroelectric tuners:

1) Coaxial geometry

2) “Planar coax” geometry

3) Sandwich-in-waveguide configuration

Designs are for 500 kW pulse power and 4 kW average (500 kW x 1.3ms x 5pps – ILC parameters)
Problems:

- somewhat bulky
- thus, it is difficult to braze both sides of ferroelectric and insulation ceramic

Tuner designs: Coaxial Geometry

23 cm

23 cm

ferroelectric

56 cm

matching ceramic

heater

water
Tuner designs: “Planar-coax” Geometry

-Simulations of full geometry show that solution has many resonances in ferroelectric and matching ceramics.

- Due to a lack of time, we’ve so far failed to find a working solution for planar coaxial geometry.

-Thus, we plan to continue…

  move parasitic mode’s frequencies far from the working mode (if possible)
  carefully design the coax-waveguide adapter not to excite parasitic modes
Tuner designs: Sandwich-in-waveguide Geometry

This version has many-mode spectrum

Versions were tried...

This variant seems to be suitable...
1) Conceptual design and electrical parameters of an L-band fast phase shifter are presented.

2) Device is based on a new ferroelectric ceramic, whose permittivity changes with external application of an electric field. The switching time depends on only the external HV circuit and can thus be less than one microsecond.

3) The phase shifter is built into a standard air-filled WR650 waveguide.

4) Calculations and measurements show the possibility of achieving a phase shift of 120°. An average switching rate of less than 0.5 ns for each degree of RF phase has been measured.

5) Pulse power capability is ~500 kW [estimated]

6) This report describes the first results of low power measurements on a one-third scale model of the phase shifter.
[design details]

- design employs a rectangular waveguide as a building block, inside of which ferroelectric ceramic bars are placed.

- to reduce the RF fields, a number of identical waveguides connected in parallel is used.
• the mode spectrum is sparse, and can be controlled easily by changing the waveguide geometry.
• the transverse section of each bar (5 × 6 mm) is dictated mostly by the dielectric constant of the ferroelectric ceramics (~460).
• the matching linear ceramic bricks having a dielectric constant of ~21 are placed before and after the ferroelectric bars.
• to match an empty entrance or exit waveguide (WR650) to the resulting sandwich-like structure, dielectric rods (ε ~9.8) are placed before and after the sandwich
• matching scheme provides for equal power flow in all the three layers.
Some parameters for 500 kW pulse power and 4 kW average 
( 500 kW x 1.3ms x 5pps – ILC parameters)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. E-field in ferroelectric</td>
<td>3.0 kV/cm</td>
</tr>
<tr>
<td>Avrg. E-field in ferroelectric</td>
<td>2.0 kV/cm</td>
</tr>
<tr>
<td>Max. E-field in ceramic</td>
<td>5.9 kV/cm</td>
</tr>
<tr>
<td>Max. E-field in air</td>
<td>6.1 kV/cm</td>
</tr>
<tr>
<td>One way phase shift</td>
<td>~ 120 deg (15 kV/cm bias)</td>
</tr>
<tr>
<td>One way loss</td>
<td>6.0 %</td>
</tr>
<tr>
<td>Ferroelectric pulse heating</td>
<td>0.2 K (deps = 0.6)</td>
</tr>
<tr>
<td>Ferroelectric average heating</td>
<td>0.9 K (deps = 2.7)</td>
</tr>
</tbody>
</table>

(Loss and heating were calculating for
5e-4 ferroelectric loss tangent and for
1e-4 other ceramics loss tangent)
geometry is well matched for different $\varepsilon$ of ferroelectric
Frequency response for new planar geometry

Calculated reflections are shown with the HV input for the bias voltage is placed in the region where the RF fields are small.

**TABLE 1. Phase Shifter Design Parameters**

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Ferroelectric permittivity (at $V_{bias} = 0$), $\varepsilon$</td>
<td>$\sim 460$</td>
</tr>
<tr>
<td>$\partial$(phase)/$\partial\varepsilon$, degree</td>
<td>$4$</td>
</tr>
<tr>
<td>Max. RF electric field ($P = 500$ kW), kV/cm</td>
<td>$5.9$</td>
</tr>
<tr>
<td>Max. DC electric field, [(\Delta(\text{phase})=120) deg], kV/cm</td>
<td>$15$</td>
</tr>
<tr>
<td>Total loss for ferroelectric loss tangent $\tan(\delta)$, %</td>
<td>$2.8 + 6 \cdot 10^3 \tan(\delta)$</td>
</tr>
</tbody>
</table>
we use 1/3 of the structure to test the tuner behaviour
MEASUREMENTS OF PHASE SHIFT FOR 1/3 MODEL

• model was fabricated for one-third of the full design and used for subsequently described measurements

• model may be disassembled in order to test a variety of ferroelectric bars.

• tests were made with gold-plated ferroelectric bars and matching slabs, and contact to the copper walls was provided by liquid InGa alloy or by indium solder.

• results of measurements of phase shift are seen to be in very good agreement with simulations.
The signal at 1,290 MHz is split in two portions, which later are combined at a mixer. The resulting signal from the mixer was detected by a diode and monitored at an oscilloscope, and also captured by a computer for further signal processing (mainly FFT). The high voltage rise/fall times from the available pulse generator were in the range of ~100 ns.

**Time-response of phase shifter.** Red curve (convex) is the difference between data with RF off and RF on. Blue curve is FFT/IFFT processed signal. Black curve (concave) is the high-voltage pulse with its peak value of ~9.7 kV. It is seen that the time delay between the peak voltage and the peak variation in phase is **28 ns**. (This value excludes delays in cables.) (The difference signal of 67 mV from the mixer corresponds to a phase change of 77º)
MEASUREMENTS OF LOSS

• Loss tangent measured for the uncoated bars (manufactured from the same batch used to make the bars coated with gold); the value is $\sim 2 \times 10^{-3}$, suggesting that the 1/3 scaled tuner model may suffer a transmission loss no better than $\sim 0.7$ dB.
• In actuality, the measured transmission lower, with the best values seen only when either freshly applied liquid InGa or soldered the bars to the waveguide walls (using In).
• We were never been able to apply more than 4 kV to the soldered configurations; hence we discuss below only the structures assembled with liquid InGa.
• In configurations with fixed structure height, when the top and bottom walls are tethered by bolting to the side walls, the transmission dropped when the voltage grew.
• In a configuration where the top wall was resting without tethering on the ceramic bars under 200-400 lbs load, the transmission did not drop so much.
Sandwich-in-waveguide geometry summary:

- Measurements for a 1/3 version of an L-band tuner give phase shifts in good agreement with theory.

- Rapid (~30 ns) switching speed was demonstrated; this could be interpreted to correspond to an average switching rate of less than 0.5 ns for each degree of RF phase.

- Excessive insertion loss was seen. It is our understanding that the losses are partially caused by the bad contact between ceramic and the waveguide walls, and is not an intrinsic property of the phase shifter.

- Lastly, the tuner was connected to a 1.3 GHz cavity and confirmed the capability of fast tuning of its resonance frequency.

- The preliminary design was developed, and further monetary support for this work has been obtained.
56 MHz Tuner

Diagram showing the components of the 56 MHz Tuner, including the Axis, Ferroelectric ring, Metal, and Insulator (oil plug). The dimensions Ø 240 and Ø 70 are indicated.
56 MHz Tuner

**Basic Parameters:**

RF (CW):

- Frequency - 56 MHz
- RF power - 10 kW
- Tuning bandwidth - 100 kHz

RF losses (Power=10 kW):

- Ferroelectric loss = 4.2% (loss. tang = 0.0005) - 420 W
- Metal loss (Cu) = 3.2% (copper) - 320 W
- Oil loss 0.23% (loss tang. = 0.002) - 23 W
- Total losses - 760 W

DC voltage (bias):

- Voltage - 7.5 kV
- Maximum frequency - 100 kHz
- Ferroelectric capacitance - 5600 pF
- Max bias current ~ 20-25 A

Cooling and DC/RF insulation:

- Transformer Oil
- RF coaxial ceramic window (Al2O3, material A-476, ε=9.6; δ=4*10^-4)
Simulation parameters:
- Ferroelectric loss $\delta = 5 \times 10^{-4}$
- Oil loss $\delta = 2 \times 10^{-3}$
- Metal: Copper

Loss: 7.5%
Phase shift: $140^\circ$
• Evolution of a fast L-band phase shifter has been described:
  – Coaxial geometry
  – Planar-coax geometry
  – Sandwich-in-waveguide configuration

• Material issues:
  – Improve tunability at low bias voltages
  – Losses in ferroelectric material need to be reduced
    • (the two issues above were present because the version of ceramic used now is a “quick modification of the X-band ceramic, and thus cannot perform well in L-band)
    • (efforts are underway by Euclid Techlabs and Ceramics Ltd to design a version for L-band [ they have secured funds already ])
  – Means of joining (brazing) ferroelectric and metal is needed
    • Let’s us emphasize that this design was for proof-of-principle experiments, and no provisions for breakdown limit improvements were employed.

• Design for a coax line 56 MHz phase shifter has been described.