Fast X-Band Phase Shifter

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Abstract. A phase shifter to be the key element of an active high-power switch is described. This phase shifter employs ultra-fast, electrically-controlled ferroelectric elements. This high-power switch will allow one to build an active Delay Line Distribution System (DLDS), which would provide substantial reduction in the length of waveguide, compared to what would be required for the traditional passive DLDS design for NLC. The results of preliminary optimization of the phase shifter at the NLC frequency of 11.424 GHz are presented showing the feasibility of building the switch to control a power of 500 MW. Initial tests at a power of up to 50 MW are planned using the Omega-P/NRL X-band magnicon.

INTRODUCTION

The current design for the linear collider NLC relies on pulse compression to achieve the high peak RF power levels required to drive the accelerator structures (~500-600 MW in 400 ns pulses) [1]. A number of rf pulse compression systems have been considered recently for collider use, including versions of the Delay Line Distribution System (DLDS) and the Resonant Delay Line Pulse Compression System SLED-II [2]. The mechanisms upon which these systems operate are passive, in that no element in the microwave circuit has time-dependant properties. The RF pulse compression or power combining in all these systems is achieved using 180° phase switching in the klystrons. Limitations of passive pulse compression systems include their low compression ratios (~4:1), limited efficiencies, and very long runs of low-loss high-vacuum waveguide [2].

In principal, the most efficient power combining system should be DLDS. However, in its original incarnation, DLDS requires ~300 km of waveguides and waveguide components [2]. It has been recognized that a substantial reduction in the length of waveguides could be achieved if an active DLDS system could be developed. Fig. 1 illustrates the layout of an active DLDS for the case of one waveguide feed for four accelerator modules [2]. The key element is a high power microwave switch, which must quickly divert ~500 MW of power sequentially from a main feed line in and out of the accelerator modules. The required peak power is achieved by adding coherently the outputs of eight 75 MW klystrons. A secondary attribute of active DLDS would be the absence of need for a pattern of fast phase shifting for the eight klystrons, thereby reducing the required klystron bandwidth.
FIGURE 1. Schematic for an active DLDS that feeds four accelerator modules [2]. In this arrangement, the fast switches would each slice one-quarter of the length out of the 1.6 µs klystron pulse, and direct the ~400 ns slices to their respective accelerator structures so as to be synchronous with arrival of the beam.

In an attempt to circumvent limitations of passive pulse compressors and traditional DLDS, various concepts of high power switches have already received attention. These involve switches with optically-varied silicon mirrors [3], PIN/NIP diode arrays [4], and plasmas [5]. As yet, none of the tested versions of these active pulse compressors have achieved high enough power levels for use with NLC: the maximum output power achieved is 10 MW in the switch using a PIN/NIP diode array active window [6], and 53 MW in a compressor employing plasma switches [7].

In the present paper, a phase shifter to be the key element of an active high-power switch is described that employs ultra-fast, electrically-controlled ferroelectric elements [8,9]. Recently, ferroelectrics have received close attention, and are already used in low- to moderate-power (up to 100 kW peak) military and communication systems as fast tunable components [10,11], because they have the ability to operate up to frequencies above 30 GHz with reasonably low losses, and have very high tuning speed. These characteristics, together with the high electric breakdown strength and good vacuum properties, make modern ferroelectrics attractive candidates for use in high-power active RF phase shifters and switches for accelerator applications.

GENERAL

1. Ferroelectrics have an \( \varepsilon(E) \) that can be rapidly altered by application of a bias voltage pulse. The switching time would be generally limited by the response time of the external electronic circuit [11] that generates and transmits the high-voltage pulse, and can thus be in the ns range. Ferroelectrics should have the following properties in order to function successfully in high-power rf switches for linear collider applications:
   - the relative dielectric constant \( \varepsilon \) should not exceed 300-500 to avoid problems in the switch design caused by interference from higher-order modes [8,9];
   - the relative dielectric constant \( \varepsilon \) should change by 10’s of percent upon application of the bias voltage to provide the required tuning range;
- bias electric fields should be of moderate amplitude, namely not more than a few 10’s of kV/cm, so as to avoid dielectric breakdown, and
- the loss tangent $\tan \delta$ should be about $10^{-3}$ or lower at 11 GHz. This is to insure that losses in the ferroelectric phase shifter will not exceed 1-2%, thereby allowing switch operation at high average power in a collider having high repetition rate. For the losses of 1% at the NLC power of 500 MW in the pulse of 1.6 $\mu$sec and the repetition rate of 120 Hz the average dissipation in the phase shifter will be less than 500 W.

Modern bulk ferroelectrics, such as barium strontium titanate (Ba$_x$Sr$_{1-x}$TiO$_3$, or BST) with $\varepsilon \sim 500$, have high enough electric breakdown strength (100-200 kV/cm) and do not require too high a bias electric field (~20-50 kV/cm) to effect a significant change (20-30%) in $\varepsilon$. Loss tangent for commercially-available samples of these materials is about $\sim 10^{-2}$ at 10 GHz [10].

Euclid Concepts, LLC recently developed and tested a modified bulk ferroelectric based on a composition of BST ceramics, magnesium compounds, and rare-earth metal oxides that has a relative permittivity $\varepsilon = 500$, and 20% change in permittivity for a bias electric field of 50 kV/cm [12]. In Fig. 2 is shown the first sample of a ring made of this material. This ring has outer diameter of 34 mm, inner diameter of 20 mm and thickness of about 8 mm. The ring dimensions are limited not by any fundamental questions, but merely by the presently-available fabrication equipment (specifically, the press-forms).

![FIGURE 2. The first sample of a ring made of BST ceramic.](image)

The loss tangent already achieved for the best samples is less than $4 \times 10^{-3}$ at 35 GHz [12], which corresponds to about $1.3 \times 10^{-3}$ at 11 GHz, assuming the well-known linear dependence between loss tangent and frequency [10]. These losses are close to what is required for operation in NLC. Development of production techniques for this material continues, with the expectation of further lowering the loss tangent to values of less than $10^{-3}$. In principle, the availability of this ferroelectric already allows one to design and build an X-band high-power RF phase shifter rated for the full peak
power of 500 MW, as required for NLC, but with a reduced repetition rate in order to avoid cooling problems.

2. Realization of an active DLDS (as shown in Fig. 1) requires development of a fast, high-power microwave switch. These switches must be able on command to redirect the full microwave power from a main feed line to one accelerator module after another within the RF pulse, with a switching time of tens of ns. One possible scheme for such a switch is shown in Fig. 3. The circuit consists of two 3-dB hybrid couplers (the passive elements), and an electrically-controlled phase shifter (the active element).

![Fig. 3. A possible arrangement of a switch for an active DLDS.](image)

In this circuit, input power is supplied to one waveguide at the left, for instance from eight 75-MW klystrons, with the second left-most waveguide terminated with a matched load to absorb reflected power. The hybrid splits the input power into two equal portions which, with the phase shifter unbiased, combine into one of the right-most output channels. In order to switch RF power from one output to the other, one has to change the phase difference between the two input signals by 180°. This change is to be provided by applying a fast rise-time bias voltage pulse across the ferroelectric elements in the high-power microwave phase shifter. This phase shifter has to be designed to operate with at least half of the full RF power (500/2 = 250 MW for NLC) in order to switch the full power of 500 MW from the first channel to the second channel. For a 400 ns pulse to be directed to each accelerator section, the rise and fall times for the switching should each be less than about 30-40 ns, so as to not contribute a substantial loss of RF energy.

3. A phase shifter design can be constituted as a set of RF cavities partially-filled with ferroelectric whose dielectric constant is electrically-controlled. A change in resonance frequency of the cavities causes a corresponding phase change for the output signal.

The proposed ferroelectric phase shifter arrangement is shown in Fig. 4. The cavities should sustain the full power of 250 MW without breakdown, and should possess low dielectric losses. These requirements limit the maximum available phase shift that can be achieved in one cavity to about ~50°. Thus, in order to achieve the required phase shift of 180°, a sequence of four identical cavities should be used. The TE_{031} cavity mode is used in order to reduce the RF field in the ferroelectric, while keeping a reasonable diameter of the ferroelectric ring. The cavities have to be designed and positioned such a way that reflections of the input signal should be minimized and transmission should be maximized within a full tuning range of 180°.
In order to achieve maximum transmission over a wide frequency range, a quarter-wave filter-like arrangement may be used [13]. In this case the distance between the cavities should be close to \( L = \left( n + \frac{1}{2} \right) \lambda_z / 2 \). Here \( n \) is an integer and \( \lambda_z = 2\pi/k_z \), where \( k_z \) is the longitudinal wavenumber in the waveguide sections between the cavities.

![Diagram of phase shifter](image)

**FIGURE 4.** The entire phase shifter conceptual layout that includes four TE\(_{031}\) cavities, coupled together with sections of TE\(_{01}\) waveguide. All dimensions are in mm.

The calculated change the phase of the transmitted signal vs. ferroelectric permittivity for the composite four-cavity phase shifter is shown in Fig. 5. One can see that this dependence is close to linear.

![Graph of phase change vs. permittivity](image)

**FIGURE 5.** Phase change of the transmitted signal vs. \( \varepsilon \).
The results for optimized parameters found for the phase shifter are listed in Table I.

TABLE I. Parameters of the phase shifter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>operating frequency, GHz</td>
<td>11.424</td>
</tr>
<tr>
<td>DC bias voltage for ~200° phase shift, kV</td>
<td>100</td>
</tr>
<tr>
<td>number of cavities</td>
<td>4</td>
</tr>
<tr>
<td>cavity operating mode</td>
<td>TE(_{031})</td>
</tr>
<tr>
<td>waveguide mode</td>
<td>TE(_{01})</td>
</tr>
<tr>
<td>maximum reflection within a full tuning range, dB</td>
<td>-27</td>
</tr>
<tr>
<td>transmitted (switched) power, MW</td>
<td>250 (500)</td>
</tr>
<tr>
<td>peak power losses ((\tan\delta = 0.0013)), MW</td>
<td>18 (3.6%)</td>
</tr>
<tr>
<td>efficiency, %</td>
<td>&gt; 96</td>
</tr>
<tr>
<td>maximum RF electric field in ferroelectric, kV/cm</td>
<td>24</td>
</tr>
<tr>
<td>maximum RF electric field in vacuum, kV/cm</td>
<td>950</td>
</tr>
</tbody>
</table>

It should be noted that further reduction of ferroelectric losses to increase the efficiency and lower the power to be dissipated is possible by improvement in the preparation of the ferroelectrics [12], by further optimizing the cavity design, and by increasing the number of cavities. All three means are planned for use in the full scale, high average power design for NLC.

4. A design concept for the phase shifter that will be suitable for high-power use is shown in Fig. 6.

![FIGURE 6](Image) A concept of a phase shifter design, showing the bias electric field lines. Dimensions are in mm.
The four cavities are located in an evacuated chamber that is external to the evacuated waveguide. In order to apply biasing voltages up to 100 kV, part of the end walls in each cavity are separated from the rest of the cavity by circular non-radiating slits. These wall segments are supported by special metallic spacer rods. These spacers are also used for applying biasing voltage from a single feed-through to all four cavities. The central parts of the cavities together with waveguides are supported by grounded supporting rods. Note that an additional small DC bias voltage (few of kV) may be applied, if necessary, in order to suppress multipactoring near the ferroelectric rings and provide initial cavity tune.

The biasing voltage built-up time is limited by the capacitance of the ferroelectric rings. In our case the overall capacitance of all four rings is about 800 pF. Thus, in order to obtain a switching time of less than 40 ns required for linear collider application, the impedance of the biasing generator must be less than about 25 Ohms.

5. Evaluation of the phase shifter with RF power levels up to 50 MW can be carried out using the Omega-P/NRL 11.4 GHz magnicon [14]. The proposed arrangement of the test bed for evaluation of the phase shifter using components developed for Omega-P active pulse compressor [5] is shown in Fig. 7.

![FIGURE 7. Arrangement for testing the phase shifter up to 50 MW.](image)

Because the magnicon has two outputs with the equal power [14], the test bed for the phase shifter doesn’t require a power splitter. Input and output of this phase shifter are circular waveguide with TE$_{01}$ mode, and consequently the circuit requires two mode converters [5] from WR90 waveguide to circular waveguide. The second magnicon output is connected to a section of WR90 waveguide. The power from the two outputs is combined in a 3-dB hybrid [5]. Finally the power from the outputs of the two hybrids is absorbed in high-power SLAC-type vacuum loads. Varying the 100 kV voltage of the biasing pulse generator will allow redirection of the full magnicon power from one output arm of the 3-dB hybrid to another.

Tests at full power level can be performed at SLAC, the only laboratory where an 11.4 GHz source with a power of 500 MW in 400 nsec pulses is presently available [15].
CONCLUSIONS

A new ultra-fast, electrically-controlled ferroelectric phase shifter has been designed as a key element of a high-power switch for an active DLDS for future linear collider. Solutions found in the design allow one to anticipate fast switching of X-band pulsed power at a level of about 500 MW, showing the possibility of developing an active DLDS for NLC.

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REFERENCES