ACTIVE RF PULSE COMPRESSOR WITH A FERROELECTRIC SWITCH*

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Abstract

Principles and preliminary design for a microwave active pulse compressor using an electrically-controlled ferroelectric switch are presented. The design of an 11.4 GHz, 500 MW pulse compressor with a pulse width of about 50 nsec and a compression ratio of 10 is described. It is planned to drive the compressor using the Omega-P/NRL X-band magnicon.

INTRODUCTION

The current design for the linear collider NLC [1] relies on pulse compression to achieve the high peak rf power levels required to drive the accelerator structures (500 - 600 MW in ~ 400 nsec pulses). A number of rf pulse compression systems have been under consideration recently including versions of the Delay Line Distribution System (DLDS) [2], Binary Pulse Compression (BPC) [3], and SLED-II [4]. The mechanisms upon which these compressors operate are *passive*, in that no element in the compressor structure has time-dependant properties. Common limitations of these systems are their relatively low compression ratio (~4:1), and/or their very long runs (100's of km) of low-loss vacuum waveguide [5]. In an attempt to circumvent these limitations, various concepts of *active* rf pulse compression have recently received attention, involving switches with optically-varied silicon mirrors [6], ferromagnetic elements [7], PIN diode arrays [8], and plasmas [9]. To date, none of the tested versions of these active pulse compressors achieved high enough power levels for use with NLC.

In the present paper, an active pulse compressor with a resonance switch based on use of electrically–controlled ferroelectric elements is presented.

GENERAL

1. Ferroelectric elements have an **E**-field-dependent dielectric permittivity $\varepsilon(\mathbf{E})$ that can be very rapidly altered by application of a bias voltage pulse. The switching time in most instances would be limited by the response time of the external electronics that generates the high-voltage pulse, and can therefore be in the nsec range. Modern bulk ferroelectrics, such as barium strontium titanate ($Ba_xSr_{1-x}TiO_3$, or BST), have high enough dielectric breakdown fields (100-200 kV/cm) and do not require too high a bias electric field (~20-50 kV/cm) to effect a significant change in ε [10]. Ferroelectrics are already successfully used in rf communication technology, radar applications, etc. Euclid Concepts, LLC recently developed and tested a bulk ferroelectric based on a composition of BST ceramics, magnesium compounds, and rare-earth metal oxides that has a permittivity ε = 500, and -20% change in permittivity for a bias electric field of 50 kV/cm. The loss tangent already achieved is close to 1.5×10^{-3} at 11 GHz [11]. Development of production techniques for this material continues, with the expectation of further lowering the loss tangent to the values of less than 1×10^{-3}. High breakdown fields, fast switching time, and already achieved low losses make ferroelectrics attractive elements for using in high-power microwave switches.

2. In active pulsed compressors with resonance switches, the rf source supplies electromagnetic energy to fill a low-loss storage cavity coupled through an electrically-controlled resonance switch to a load (the accelerating structure). Compressor operation involves two steps: *first*, that of energy storage when the coupling to the storage cavity is small in order to provide good efficiency of filling; and *second*, that of energy extraction when the coupling is high to provide fast energy discharge into the accelerating structure. The coupling of the storage cavity with the rf source is controlled by changing the resonance frequency of the switch cavity. In general, it is possible to provide a fast change of resonance frequency of the cavity by rapidly changing the rf properties of an active element situated within the cavity. A schematic diagram of a proposed active pulse compressor is shown in Fig. 1. This example is based on the design of Omega-P's two-channel Active Bragg Compressor (ABC) [12] that employs resonance plasma switches. As shown in Fig. 1, two cylindrical TE_{01}-mode storage cavities (*8*) are each terminated with an adjustable short (*9*) at one end, and an electrically-controlled switch cavity (*7*) at the other end. Waveguides (*4* and *5*) are fed from the rf source (*1*) after the source power is split using a 3-dB hybrid coupler (*3*). Mode converters (*6*) transform the mode from TE_{10}-rectangular to TE_{01}-circular. Compressed output pulses are combined and absorbed in the load (*2*). This scheme is similar to SLED [13] but for the addition of active elements (i.e., the switch cavities). Employment of the Omega-P/NRL X-band magnicon [14] that is designed for a maximum output power of about 50 MW in a 1 μsec pulse as a power source feeding the active pulse compressor described here allows one to anticipate a

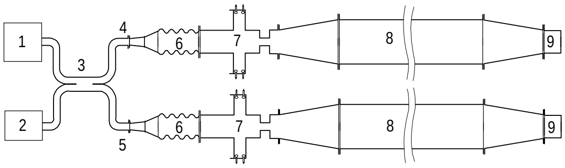

Figure 1. Schematic diagram of the two-channel ABC.

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maximum output power of 500 MW in the compressed pulse. The main design parameters of the proposed active pulse compressor are given in Table I.

Table I. Parameters of the active pulse compressor.

operating frequency f_0	11.424 GHz
input power P_o	50 MW
input pulse duration t_f	1 µsec
power gain k	10
peak output power $P_{out} = kP_o$	500 MW
output half-height pulse duration $t_{0.5}$	~40 nsec

3. To determine the switch cavity parameters, it is necessary to calculate optimal coupling of the storage cavity in both operating regimes, namely in the energy storage regime and the energy extraction regime. All calculations have been carried out for the existing ABC storage cavities [12], even though superior performance could be anticipated from improved design of the cavities. The TE_{01} energy storage cavities have lengths of about 2 m including tapers and diameters of 8 cm; their measured self quality factors Q_0 are 110,000. Optimal coupling in the energy storage regime is determined by maximizing the filling efficiency. The efficiency η for energy transfer to the storage cavity is [15]

$$\eta = \frac{2\beta\tau_o}{t_f(1+\beta)^2}\left(1-\exp\left(-\frac{t_f(1+\beta)}{\tau_o}\right)\right)^2, \qquad (1)$$

where β is the coupling, and $\tau_o = 2Q_o/\omega$ is the self time constant for the storage cavity. For parameters listed in Table I, the optimal coupling β is 4.2, which corresponds to a maximum efficiency of 64%. The coupling in the energy extraction regime is found to be

$$\beta_{out} = \frac{1}{2\eta}\frac{P_{out}}{P_o}\frac{\tau_o}{t_f} = \frac{k}{2\eta}\frac{\tau_o}{t_f}. \qquad (2)$$

For the case considered here, $\beta_{out} = 25$. The time constant τ_{out} in the energy extraction regime is $\tau_{out} = \tau_0/(1+\beta_{out})$ = 123 ns, and the half-height pulse duration $t_{0.5}$ in this case is 43 nsec. The switch cavity is a two-port element inserted between the storage cavity and the mode converter; it is characterized by transmission coefficient T, that is related with the coupling β in the following way:

$$T^2 = \beta\frac{4L}{v_{gr}\tau_0}, \qquad (3)$$

where v_{gr} is the average group velocity in the storage cavity, L is the storage cavity length. In the case considered (L=2 m and v_{gr} ~c), $T^2 \approx 9\cdot10^{-3}\beta$. Thus, the switch cavity transmission should be –14 dB in the energy storage regime, and –6.5 dB in the energy extraction regime.

4. As a result of simulation of the model switch cavity partially filled with ferroelectric (as shown in Fig. 2) two mode families were found. The first family, which are labeled "vacuum modes," are exemplified by tuning curves #1 in Fig. 3; these have a small electric field in the ferroelectric, and thus their resonance frequencies don't depend sensitively on ε. The second family, which are labeled "ferroelectric modes," are exemplified by curves #2 in Fig.3; these have high electric field in the ferroelectric and thus, their resonance frequencies exhibit a strong dependence of the frequency on ε. One can see that the resonance frequencies on curve #2 change by ~10% when ε changes by 20%. Consequently, the ferroelectric mode could be controlled with weaker applied electric field than the vacuum mode.

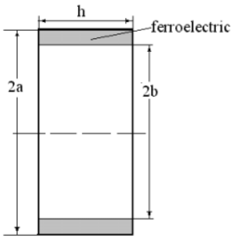

Fig. 2. The model switch cavity schematic.

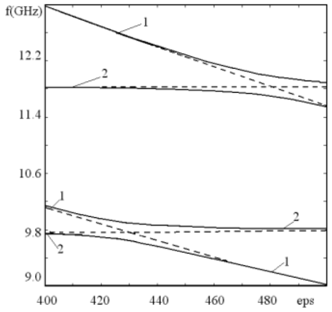

Fig. 3. The model cavity spectrum *vs.* ferroelectric permittivity ε for a=56 mm, b=53 mm and h=20 mm.

5. For the proposed 500 MW, 11.424 GHz active pulse compressor, where an available ferroelectric with ε = 500 [11] is to be used, the resonance frequency of the switch cavity for the ferroelectric mode changes by ~1 GHz while ε changes from 400 to 500, but the resonance frequency for the vacuum mode changes by only ~70 MHz. Unfortunately, the maximum electric field in the ferroelectric for the ferroelectric mode would be about 350-370 kV/cm, which is much higher than the field for

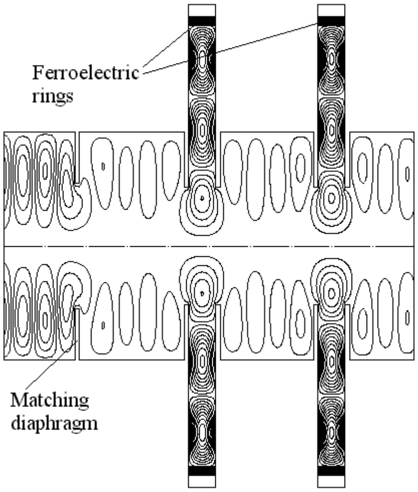

Fig. 4. The switch conceptual layout.

vacuum mode (15-20 kV/cm), and far above the breakdown limit of ~100 kV/cm. As a consequence, the vacuum mode is the only choice to be the operating mode for this type of active pulse compressor. Parameters found for the switch cavity are listed in the Table II.

Table II. Parameters of TE_{031} switch cavity.

operating frequency, GHz	11.424
operating mode	TE_{031}
cavity length, mm	20
coupling iris diameter, mm	30
coupling diaphragm thickness, mm	3
ferroelectric ring length, mm	20
ferroelectric ring inner diameter, mm	106
ferroelectric ring thickness, mm	3
transmission in energy extraction regime (ε = 400), dB	0
transmission in energy storage regime (ε = 500), dB	-4
maximum electric field in ferroelectric in energy extraction regime, kV/cm	20
maximum electric field in ferroelectric in energy storage regime, kV/cm	10
maximum electric field in vacuum in energy extraction regime, kV/cm	865
maximum electric field in vacuum in energy storage regime, kV/cm	675

The entire proposed ferroelectric switch arrangement is shown in Fig. 4, including the matching diaphragm and two TE_{031} switch cavities with ferroelectric rings, because in the switch containing only one cavity the electric field in the ferroelectric is still too high even for the vacuum mode. .

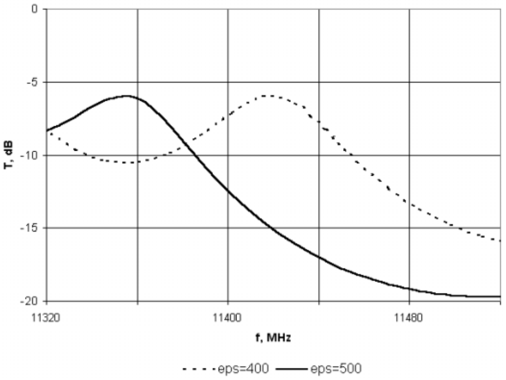

Fig. 5. Transmission *T vs.* frequency in the energy storage regime (solid curve), and the energy extraction regime (dashed curve).

The diameter of the matching diaphragm (see Fig. 4) is 30 mm and its thickness is 3 mm, to provide -6.5 dB isolation in the energy extraction regime. The frequency dependences of transmission for the energy storage and energy extraction regimes for the entire system that includes the matching diaphragm and the two switch cavities are shown in Fig. 5. The solid curve corresponds to the energy storage regime, when both switch cavities have resonance frequencies of about 11.350 GHz, and transmission at the operating frequency is about –14 dB. In the energy extraction regime (dashed curve), the ferroelectric permittivity of the switch cavities is decreased from 500 to 400, and the resonance frequencies are close to the operating frequency. At resonance the self transmission of both cavities is close to 0 dB, and the matching diaphragm provides the desired transmission of –6.5 dB at 11.424 GHz. The bias pulse electric field of 50 kV/cm is applied to the ferroelectric ring along the axial direction. The switching time in the compressor is limited by the time which is necessary to charge the capacitance of the ring and surrounding structure up to the full voltage of 100 kV. This capacitance is in range 180 – 220 pF for ε = 400 – 500. So, in order to get a rise time of about 10 ns for a capacitance of 200 pF, the biasing generator impedance should be about 25 Ohms.

DISCUSSION

A new ferroelectric switch has been designed for installation in the existing double-channel Active Bragg Compressor structure already built by Omega-P for evaluating plasma switches [12], and which is installed at the NRL X-band magnicon test facility.

In addition to the main goal of achieving a compression ratio higher than that available with passive compressors, this new switch could also allow rapid variations, during both the incident and compressed rf pulses, in the coupling between an rf energy storage cavity, the load and the rf source. This attribute would lead to an increase in energy efficiency, and an improved shape of the output pulse, compared to a switch with only binary coupling coefficients.

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