ONE-CHANNEL, MULTI-MODE ACTIVE PULSE COMPRESSOR*

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Abstract

Basic studies of factors that limit RF fields in warm accelerator structures require experiments at RF powers that can be produced using pulse compression. This approach is being implemented to compress output pulses from the Yale/Omega-P 34-GHz magnicon to produce ~100-200 MW, 100 ns pulses. A new approach for passive pulse compression is a SLED-II type circuit operating with axisymmetrical modes of the TE0n type that requires only a single channel instead of the usual double channel scheme. This allows one to avoid a 3-dB coupler and need for simultaneous fine tuning of two channels. A 30 GHz passive prototype was tested at low power level in order to demonstrate key principles. The prototype showed a power gain 4.5 at a compression ratio 6:1 for an efficiency 63%. An active version of the one-channel pulse compressor is also suggested. It is attractive due to the possibility to achieve higher power gain. The active version naturally requires an electrically controlled coupler. In particular, as active elements of the coupler we suggest to use either gas filled discharge tubes or ferroelectrics.

INTRODUCTION

Development of high-gradient accelerating structures for a future normal conducting e^--e^+ linear collider requires high-power RF sources at frequencies 10-34 GHz [1]. These sources are necessary in order to organize full-scale testing of the accelerating structures which have to work at extremely high fields providing acceleration above ~100 MeV/m. Typical required powers for such tests fall in the range of 100-200 MW with a pulse width of 100 - 200 ns. This power level can be achieved by creation of a longer pulse with an RF source and then employing an RF pulse compressor that transforms the long pulse into a shorter pulse of higher peak power.

SLED-II pulse compressors at X-band that consist of two multi-mode delay lines connected by a 3-dB coupler have allowed a record achievement of about 600 MW peak power with flat-top pulses of 400 ns duration [2-3].

One drawback of the classical SLED-II pulse compressor is its requirement for two long, identical, delay lines. A 3-dB hybrid coupler is also required, and may be considered a serious challenge for a millimeter-wave SLED-II pulse compressor, because of the impossibility at the high power levels of using single mode rectangular waveguide. Thus, there is the need for a compact quasi-optical design for a pulse compressor that can provide flat-top output pulses at mm-wavelengths.

ONE-CHANNEL COMPRESSION SCHEME

A schematic drawing of the new pulse compressor is shown in Fig. 1. It is an axisymmetric multi-mode cavity which effectively operates in a near-reflectionless traveling-wave mode [4,5]. The traveling-wave eigen-mode in the pulse compressor consists of the TE_{02} mode propagating one way (left-to-right in Fig. 1) and the TE_{03} mode propagating the other way (right-to-left in Fig. 1). Mutual mode converters (elements 1 in Fig. 1) at each end of the cavity convert one of these modes into the other by means of selective reflecting converters. The input (output) wave is in the TE_{01} mode, and enters (leaves) at the left (right). The left-to-right traveling TE_{01} mode is coupled only with the left-to-right traveling TE_{02} mode by means of a selective mode converter (element 2) placed in the middle of the cavity. This converter plays the role of an input coupler and must provide the optimal level of conversion $TE_{01} \rightarrow TE_{02}$ in order to obtain high compression efficiency. The right-to-left traveling TE_{03} mode must not be perturbed by the $TE_{01} \rightarrow TE_{02}$ coupling converter.

The input fed TE_{01} wave propagates to the $TE_{01} \rightarrow TE_{02}$ mode coupler, where a part of the incident power is converted into the forward TE_{02} wave. The TE_{02} wave then propagates to the right $TE_{02} \leftrightarrow TE_{03}$ reflecting converter and is completely transformed into the TE_{03} wave, which propagates to the left end reflector without change. At the left end the TE_{03} mode has full conversion into the forward TE_{02} mode. At the $TE_{01} \rightarrow TE_{02}$ mode converter this wave is added constructively to a new portion of power incident in the feeding forward TE_{01} mode. So, like in any SLED-II pulse compressor, RF power builds up inside the compressor. The transmitted signal in the TE_{01} mode decreases, so long as the input phase remains constant. When the 180° phase flip occurs in the compressor the stored power begins to leak out, being in the same phase that of the incoming TE_{01} power. This amounts to an emissive burst of RF power at the output. This amounts to pulse compression. From this point of view this compressor works like well-known SLED-II compressor and much of the theory created for SLED-II is applicable [2,3].

It is assumed that both the $TE_{02} \leftrightarrow TE_{03}$ reflective mutual mode converter and the $TE_{01} \rightarrow TE_{02}$ selective mode coupler must be broadband enough to accommodate the pulse spectrum width $\Delta\omega$, which is approximately equal to $\Delta\omega = 2\pi/\tau_{out}$, where τ_{out} – is an output pulse duration.
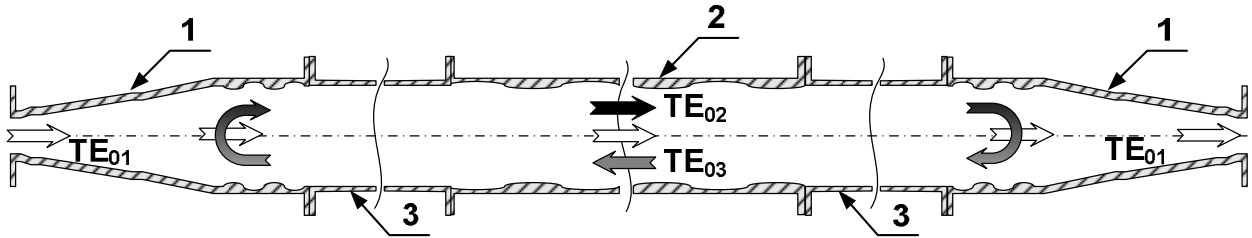
Figure 1: One-channel SLED-II pulse compressor. 1 - $TE_{02} \leftrightarrow TE_{03}$ reflective mode converter; 2 - $TE_{01} \to TE_{02}$ transmission mode converter; 3 – waveguide delay lines.

TE02-TE03 reflective mode converter

This mode converter consists of several sections, as shown in Fig. 2. The TE_{02} mode is incident from the left. In the first corrugated section the incident mode is converted into a mixture of 50% TE_{03} and 50% TE_{02}. The next part is a narrowed section which totally reflects the TE_{03} mode because the following cylindrical section is cut off for the TE_{03} mode. The TE_{02} mode propagates through this section while accumulating a phase shift. This TE_{02} mode is reflected by the next down taper. Therefore, in the corrugated section the returning 50% TE_{02} mode is converted into TE_{03} mode, and merges completely with the first 50% TE_{03} mode due to proper phase differences provided by choice of a proper length for the aforementioned cylindrical section.
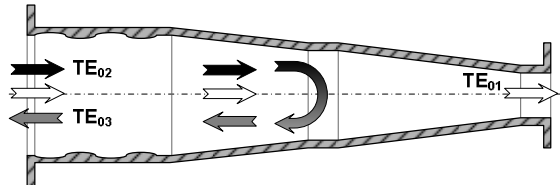

Figure 2: $TE_{02} \leftrightarrow TE_{03}$ mode converter-reflector.

TE01-TE02 mode converter

This element is depicted in Fig. 3. It plays the role of a directional coupler, satisfying three conditions simultaneously, namely (*i*) the forward TE_{01} mode should provide necessary coupling with the forward TE_{02} mode (for example, for compression ratio $C_r = 6$ the conversion must be 50%) without losses into other modes; (*ii*) the backward TE_{03} mode should propagate without diffraction losses; and (*iii*) the forward TE_{02} mode should not have significant scattering into other modes except the forward TE_{01} mode.
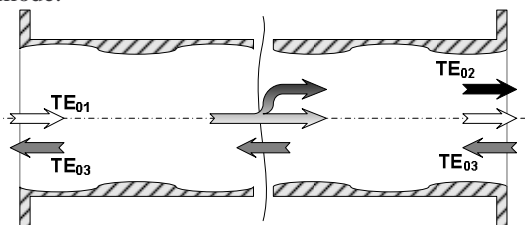

Figure 3: TE_{01}-TE_{02} selective directional coupler.

For active compression the TE_{01} TE_{02} mode converter should be replaced by an active coupler. Such a coupler works in the passive regime before switching. In the post-switched condition this coupler should provide a full conversion of the stored TE_{02} mode into output TE_{01} mode. In order to provide these conditions we suggest a three-section scheme as shown in Fig. 4, where a switch based on plasma discharge tubes is shown. Each of the first and third sections is identical to the TE_{01} TE_{02} mode converter which was already described. The intermediate section is actually a phase shifter. Let us assume that the first section provides 50% conversion of TE_{01} into TE_{02} (or TE_{02} into TE_{01}). However, the resulting conversion at output of the third section strictly depends on a mutual phases of TE_{01} and TE_{02} modes arising in the second section. This fact is illustrated by Fig. 5 where output powers of TE_{01} and TE_{02} modes are plotted. Conversion curves are periodic functions of the mutual phase $\Delta\varphi$. In particular, if incident mode is TE_{01}, then a mutual phase $\Delta\varphi = 2\pi n$ (*n* – is an integer) signifies full conversion into the TE_{02} mode. If $\Delta\varphi = \pi n$ (where *n* is an odd integer), mode conversion is absent.

Therefore, point **A** in Fig. 5 should be chosen as an operating point in the power storage regime. In order to extract the power stored in the compressor, the active phase shifter should provide transition from point **A** to point **B**. This means that $\pi/2$ additional phase due to the plasma discharge is necessary.
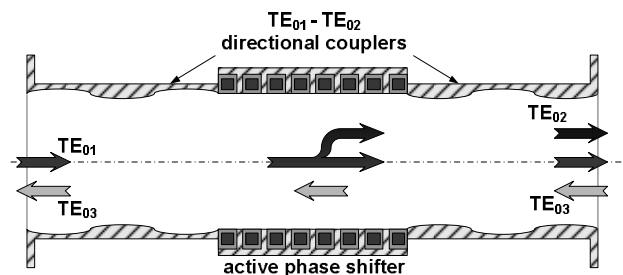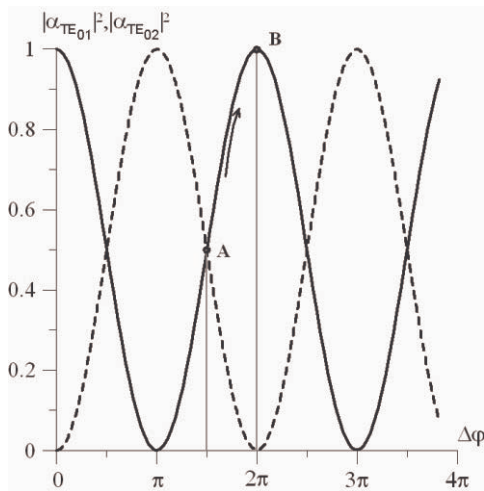

Figure 4: Active RF switch based on plasma tubes.

Figure 5: Powers of TE_{01} and TE_{02} modes in dependence on mutual phase brought by active section: the solid curve is TE_{02} mode power, the dashed curve is TE_{01} mode power.

Figure 6: Oscillograms of the incident (1) and compressed output pulses (2) in a case of 180° phase flip ($Cr = 6$, $G = 4.5$).

The necessary phase shifting section can be also obtained from ultra-fast, electrically controlled ferroelectric elements. Such a phase shifter was elaborated upon by Omega-P for use at X-band. Note, that the loss tangent for Ka-band ferroelecrics is $6\text{-}8\times10^{-3}$, and the tuning range is 20% (i.e., the dielectric constant will drop from 550 to 440 when the bias field of 50 kV/cm is applied). Response time is better than 10 nsec. The minimum ring thickness may be 0.6 mm at a diameter of 70 mm. Breakdown limit is 200 kV/cm.

LOW POWER TESTS

A 30 GHz passive prototype of the one-channel compressor was tested in order to demonstrate key principles of operation [5]. The investigated compressor included two $TE_{02}\leftrightarrow TE_{03}$ reflectors, a $TE_{01}\rightarrow TE_{02}$ mode converter, and a waveguide section of variable length for fine tuning. Each reflector also had a central section in a form of movable plunger which allowed changes in mutual phases of $TE_{02}\text{-}TE_{03}$ modes and, thus, to tune the conversion efficiency. To simplify the first test, long delay line waveguides were excluded, and the total length of the compressor was 1200 mm (loaded Q-factor was 2×10^{3}). Thus, taking into account group delays, the resulting round trip delay time was about 13 ns. RF power was delivered to the compressor by means of Marie mode transformer, and at the output of compressor a serpentine $TE_{01}\text{-}TE_{11}$ mode converter was used.

In the test we used a 180° phase flip which was provided by means of controllable p-i-n diode. The diode provided 180° phase switching in approximately 5 ns. Note that this time is comparable with round trip time (13 ns). Nevertheless, a power gain of $G = 4.5$ was reached with ~60% efficiency. Typical oscillograms of the incident and compressed pulses are shown in Fig. 6.
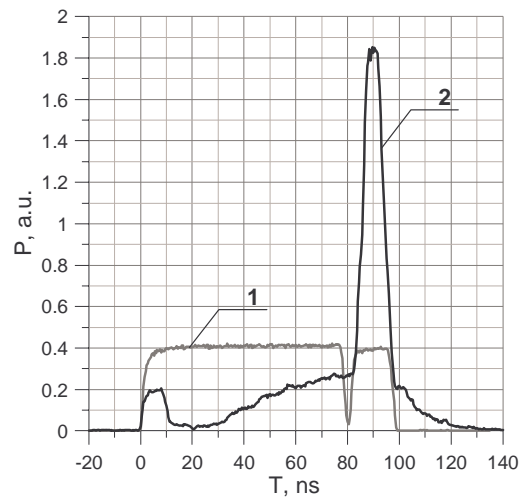
CONCLUSION

The proposed pulse compressor is based on a matched cavity operating with a superposition of the three lowest axis-symmetrical modes. Unlike the usual SLED-II compressor, two channels are replaced by a single channel, and need for a 3-dB coupler is avoided. Since all modes in the compressor are so-called "breakdown proof," a very high power level should be achievable with this circuit.

An active version of this pulse compressor, based on use of an electrically controlled mode coupler, promises power gains which could be 2-3 times greater than the power gain of passive circuit.

Low power tests that were carried out show operation of the compressor circuit with good agreement between the measured and calculated parameters.

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