HIGH-POWER RF PULSE COMPRESSION WITH SLED-II AT SLAC*

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Abstract

Increasing the peak rf power available from X-band microwave tubes by means of rf pulse compression is envisioned as a way of achieving the few-hundred-megawatt power levels needed to drive a next-generation linear collider with 50–100 MW klystrons. SLED-II is a method of pulse compression similar in principal to the SLED method currently in use on the SLC and the LEP injector linac. It utilizes low-loss resonant delay lines in place of the storage cavities of the latter. This produces the added benefit of a flat-topped output pulse. At SLAC, we have designed and constructed a prototype SLED-II pulse-compression system which operates in the circular TE_{01} mode. It includes a circular-guide 3-dB coupler and other novel components. Low-power and initial high-power tests have been made, yielding a peak power multiplication of 4.8 at an efficiency of 40%. The system will be used in providing power for structure tests in the ASTA (Accelerator Structures Test Area) bunker [1]. An upgraded second prototype will have improved efficiency and will serve as a model for the pulse compression system of the NLCTA (Next Linear Collider Test Accelerator).

I. INTRODUCTION

Originally conceived by Fiebig and Schieblich [2] in 1988 and independently developed by Farkas, Wilson and Ruth [3] at SLAC, SLED-II is an extension of the SLED [4] pulse compression technique. SLED uses high-Q resonant cavities to store energy during most of the duration of the incoming pulse. One compressed-pulse-time from the end, the phase of the input is reversed. The field reflected from the coupling interface then adds constructively with the field emitted from the charged cavity, and the stored energy is extracted. The cavities are implemented in pairs and fed through a 3-dB coupler so that the outgoing power is directed away from the source. A distinctive feature of the SLED output is the exponential spike of the compressed pulse, characterized by the time constant of the cavities.

In SLED-II, the resonant cavities are replaced by long resonant delay lines. These can be lengths of low-loss waveguide, shorted at one end and iris-coupled to adjacent ports of a 3-dB coupler at the other. The length

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of the delay lines is determined by the desired width of the compressed pulse and must be an integer number of guide half-wavelengths. As the wave emitted from the lines changes amplitude at discrete time intervals, given by the round-trip travel time, a flat output pulse can be produced. This makes SLED-II useful for the acceleration of long trains of bunches. It also increases intrinsic efficiency and reduces the peak-to-average field ratio in the compressed pulse.

II. THEORY

Let s be the iris reflection coefficient. Let t_d be the delay time given by $2L/v_g$, where L is the delay line length and v_g the group velocity in the line. Define an integer compression ratio C_r as the ratio of the input pulse length to t_d. Finally, let 2τ represent the round-trip field attenuation parameter. Then, during the time interval beginning at $t = nt_d$, the emitted field for constant input E_i can be expressed as

$$E_e(n) = \frac{\left(1 - s^2\right) e^{-2\tau}}{1 - se^{-2\tau}} \left(1 - s^n e^{-n2\tau}\right) E_i.$$

Superposition with the iris reflection yields the output

$$E_{out}(n) = E_e(n) - sE_i, \qquad n = 0, 1, ..., C_r - 2.$$

At time $t = (C_r - 1)t_d$, the phase of the input pulse is shifted by π, so that the waves add and we get a compressed output pulse of duration t_d with amplitude

$$\begin{aligned}
E_p = E_{out}(C_r - 1) &= E_e(C_r - 1) + sE_i \\
&= \left\{ \frac{\left(1 - s^2\right) e^{-2\tau}}{1 - se^{-2\tau}} \left[1 - (se^{-2\tau})^{C_r - 1}\right] + s \right\} E_i.
\end{aligned} \qquad (1)$$

For a given C_r and τ, s can be chosen to maximize E_p. The power gain and compression efficiency are

$$G = (E_p/E_i)^2, \qquad \text{and} \qquad \eta_{pc} = G/C_r. \qquad (2)$$

The theoretical limit on G is nine. Realizable systems with finite compression ratios will have somewhat lower capabilities. There is an inherent inefficiency of this method due to power emerging before and after the compressed pulse. A table of the optimized iris reflection, ideal gain, and intrinsic efficiency η_i for several compression ratios is given in Table A. The effect of component losses can be considered as the efficiency η_c of round-trip reflected transmission through the coupler and an efficiency η_L due to the delay line loss. The latter is plotted versus round trip power transmission in the delay lines for different compression ratios in Figure 1. The efficiency of

pulse compression can then be thought of as

$$\eta_{pc} = \eta_i \eta_c \eta_L. \qquad (3)$$

Table A

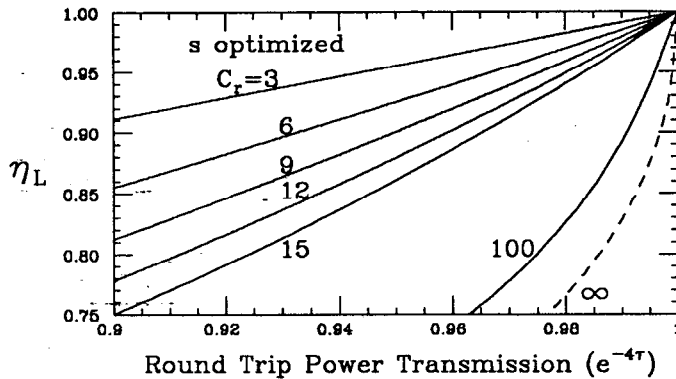| C_r	s_{opt}	G_{ideal}	η_i
2	.500	1.56	.781
3	.548	2.66	.887
4	.607	3.44	.860
6	.685	4.48	.746
8	.733	5.15	.644
10	.767	5.62	.562
12	.792	5.98	.499

Figure 1. Compression efficiency of delay lines with optimized s.

III. COMPONENTS

The schematic layout of our SLED-II system is shown in Figure 2. The frequency of operation is 11.424 GHz. Overmoded waveguide is used to keep transmission loss down and to achieve low-loss high-power delay lines. The TE_{01} mode in circular guide was chosen for its unpolarized nature as well as for the fact that its attenuation constant drops faster with increasing guide radius than that of any other low mode, quickly becoming the smallest.

As the klystron output and load or structure input utilize rectangular (WR-90) waveguide in the fundamental TE_{10} mode, efficient mode transducers between this and our circular mode are a necessary part of the system. Rather than standard Marié transducers, we use a compact design based on an old KU-band device and developed at SLAC. This component is described in detail in reference [5].

The TE_{01} 3-dB coupler was also designed and built at SLAC.[6] It is basically a copper block, about a meter in length, with two closely spaced 1.75″-diameter bores

connected by a longitudinal coupling slot. The slot is introduced and removed adiabatically to preserve mode purity. The proximity of the coupler guides necessitates circular waveguide offsets to further separate the axes and allow connection to other components. These were designed using generalized telegraphist's equations to minimize mode conversion. This prototype coupler requires its own vacuum manifold because it was machined in halves and bolted together.
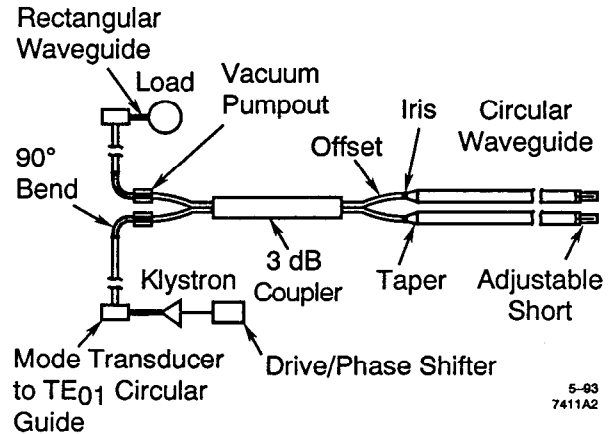
Figure 2. Schematic of high-power SLED-II system.

The irises were designed by the KKY method as described in reference [7]. They are inserted before the tapers where excited higher order TE_{0n} modes are cut off. A reflection coefficient of about 0.8 was chosen in anticipation of running with a compression ratio of 12 for structure tests. The irises were machined from stainless steel flanges and copper plated for improved conductivity.

The delay lines are each composed of about 33′ of OFHC copper circular waveguide. Non-linear tapers between the 1.75″ diameter used in the rest of the system and the 2.81″ diameter (for reduced wall loss) of the delay lines were provided by General Atomics, San Diego, CA. The same company provided the corrugated 90° bends used in the power transfer lines. Vacuum feedthroughs at the ends of the delay lines allow us to electronically tune aluminum shorting plungers. This is done via MDC stepping motors controlled with a PC. Finally, the system is evacuated via pump-out vacuum manifolds inside which the waveguide is interrupted by 6″ stacks of 15 carefully aligned copper rings with support rods recessed from the inner diameter. The gaps do not disturb the TE_{01} mode, as it involves no longitudinal currents.

IV. EXPERIMENTAL RESULTS

Non-vacuum tests were made first, with power levels of a few hundred milliwatts. The shorts were placed on the offsets to measure the transmission loss from the input port to the final output port of the 3-dB coupler.

The round-trip loss of the coupler with offsets was determined to be approximately $7.5\% \pm 1\%$ ($\eta_c \simeq 0.92$). The iris reflection coefficients were calculated from power measurements to be 0.805 ± 0.005. The loss per round trip in either delay line was determined from the steady state backwards wave to be about $4.6\% \pm 0.3\%$, and the delay time confirmed to be 75ns. The delay line waveguide, taken from an old experiment, has imperfections, resulting in less-than-ideal performance.

The SLED-II system was then assembled with the mode transducers on the pump-outs and a PSK (phase shift keyer) in our drive system. The shorts were adjusted differentially to minimize reflected power and together to maximize compressed power. The power gain was measured for different compression ratios as plotted in Figure 3. (Note: s not optimized for each C_r.) The measurements are consistent with the measured component losses, as shown by the solid curve. An output waveform recorded for $C_r = 12$ is shown in Figure 4.
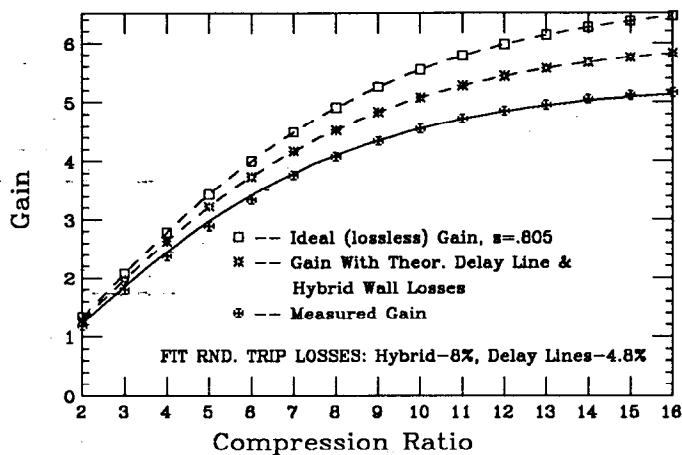

Figure 3. Measured performance of SLED-II versus ideal. The solid line fit is expected for the indicated component losses.

The input was then connected to an X-band klystron via a run composed mostly of $1.75''$ circular guide as indicated in Figure 2., and the output was connected to a high-power water load. The system was pumped down to the 10^{-8}Torr range and successfully run with power levels reaching 16 MW. This power level was limited by the time we had for rf processing, due to competing programs. We expect to run at considerably higher power in the near future.

V. FUTURE MODIFICATIONS

In the coming months, we plan to overhaul our SLED-II system, incorporating improved components. The $2.81''$ diameter waveguide of the delay lines will be replaced by $4.75''$ guide, whose attenuation constant is a factor of five less. With careful joint connection, this should significantly reduce their loss, despite our doubling

their length to test a longer fill-time structure. New shorting plungers will contact the wall in places to maintain better perpendicularity with the guide axis. The 3-dB coupler will be replaced either by a more compact, better machined, vacuum-brazed model, or by a rectangular waveguide coupler attached to four of our successful mode transducers. The 90° bends may also be replaced by rectangular guide and mode transducers. Finally, new pumpout sections will be engineered and possibly be included in the delay lines. It is hoped that this second prototype will have adequate efficiency to meet the goals of a SLED-II system for the NLCTA [8].
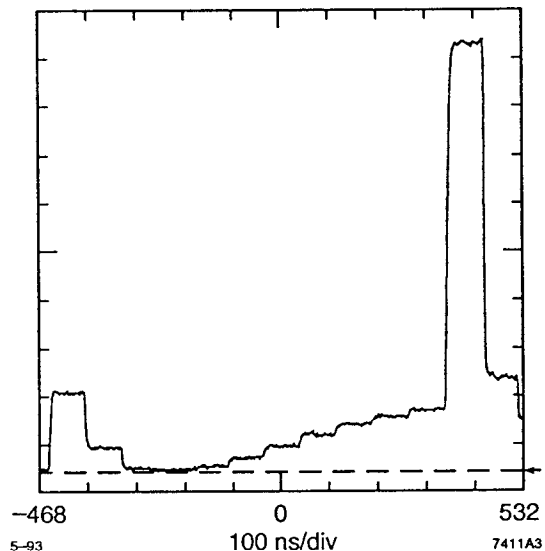

Figure 4. Output waveform for $C_r = 12$.

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