Active radio frequency pulse compression using switched resonant delay lines

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Abstract :

This paper presents a study and design methodology for enhancing the efficiency of the SLED II rf pulse-compression system [1]. This system employs resonant delay lines as a means of storing rf energy. By making the external quality factor of these lines vary as a function of time, the intrinsic efficiency of the system can reach 100%. However, we demonstrate a considerable increase in efficiency even if the change of the quality factor is limited to a single event in time. During this event, the quality factor of the lines changes from one value to another. The difference between these two values is minimized to simplify the realization of the quality factor switch. We present the system optimum parameters for this case. We also show the extension of this system to two events in time, during which the quality factor of the line changes between three predetermined states. The effects of the losses due to the delay lines and the switch used to change the quality factor are also studied.

I. INTRODUCTION

The SLED II pulse compression system employs high-Q resonant delay lines to store the energy during most of the duration of the incoming pulse. The round trip time of an rf signal through one of the lines determines the length of the compressed pulse. To discharge the lines, the phase of the incoming pulse is reversed 180°, so that the reflected signal from the inputs of the lines and the emitted field from the lines add constructively, thus forming the compressed high-power pulse.

The SLED II system suffers from two types of losses that reduce its intrinsic efficiency. During the charging phase, some of the energy is reflected and never gets inside the line. Also, after the phase is reversed, the energy inside the line is not discharged completely during the compressed pulse time period. These two effects make the intrinsic efficiency of SLED II deteriorate very rapidly as the compression ratios increases [1]. Increasing the coupling of the line just before the start of the output pulse will reduce the amount of energy left over after the output pulse is finished. This allows more energy to get out of the storage line during the compressed pulse. Losses due to reflection are reduced by keeping the line coupling as a constant value that is optimized for maximum energy storage during the charging phase. If the coupling during the charging phase is a function of time, then all the energy during the charging phase can be stored in the line. However, it will be shown in Sec.II that if the line coupling changes only once during the charging phase, a charging efficiency close to 100% can be achieved. Indeed, with two changes in the line coupling, the first during the charging phase and the other just before the discharging phase, intrinsic efficiencies greater than 90% can be achieved for reasonably high compression ratios.

We first introduce a theory for optimizing the efficiency of the pulse compression system using a single change in line coupling. We then study the situation of two changes.

II. THEORY OF SINGLE-TIME-SWITCHED RESONANT DELAY LINE

A. SLED II

Consider the waveguide delay line with a coupling iris shown in Fig.1.

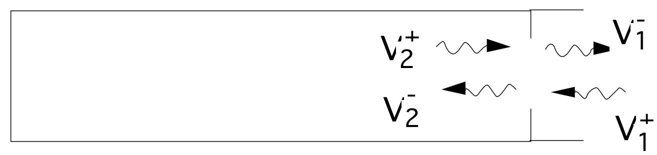

Figure 1. Resonant delay line.

The *lossless* scattering matrix representing the iris is unitary. At certain reference planes, it takes the following form:

$$\underline{\underline{S}} = \begin{pmatrix} -R_0 & -j(1-R_0^2)^{1/2} \\ -j(1-R_0^2)^{1/2} & -R_0 \end{pmatrix} \quad . \qquad (1)$$

In writing Eq. (1) we assumed a symmetrical structure for the iris two-port network. With the exception of some phase change, the incoming signal V_2^+ at time instant t is the same as the outgoing signal V_2^- at time instant $t-\tau$, where τ is obviously the round trip delay through the line; i.e.,

$$V_2^+(t) = V_2^-(t-\tau)e^{-j2\beta l} \qquad (2)$$

where β is the wave propagation constant within the delay line, and l is the length of the line. During the charging phase we assume a constant input, i.e., $V_1^+(t) = V_{in}$ which equals a constant value; If the delay line has small losses, where β has a small imaginary part, then at resonance the term

$$e^{-j2\beta l} = -p \quad , \qquad (3)$$

where p is a positive real number close to 1. Hence, we have

$$V_1^-(i) = -V_{\text{in}}\left[R_0 - (1-R_0^2)\frac{1-(R_0 p)^i}{1-R_0 p}p\right] \quad . \qquad (4)$$

In Eq. (4), $V_1^-(i)$ means the ingoing wave in the time interval $i\tau \le t < (i+1)\tau$ and $i = 0,1,2,\ldots$. After the energy has been stored in the line it is possible to dump part of the energy in a time interval τ by flipping the phase of the incoming signal just after a time interval $(n-1)\tau$; i.e.,

$$V_1^+(t) = \begin{cases} V_{\text{in}} & 0 \le t < (n-1)\tau \\ -V_{\text{in}} & (n-1)\tau \le t < n\tau \\ 0 & \text{otherwise.} \end{cases} \qquad (5)$$

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The output pulse level during the time interval $(n-1)\tau \le t < n\tau$ is then

$$V_{\text{out}} = V_1^-(n-1) = V_{\text{in}}\left[R_0 + (1-R_0^2)\frac{1-(R_0 p)^{n-1}}{1-R_0 p}\,p\right]. \quad (6)$$

This is the essence of the SLED II pulse compression system. The optimum values of the iris reflection coefficient such that V_{out} is maximized for a given value of n are given in Ref. [1].

If a *high-power* rf switch existed, it would be possible to have 100% efficiency. This switch would have to change the iris reflection coefficient in a time δt such that $\delta t << \tau$. Most applications that utilize such pulse compression techniques employ very high-power rf fields; but high-power switches are not readily available and are still a subject of extensive research. It is foreseen that an optical high-power rf switch can be developed to switch at least once every few milliseconds [2].

Switching the system *once* can definitely improve its efficiency. There are two possibilities. First, the iris reflection coefficient can be changed during the charging time to put more energy in the line. Second, the system can be switched just before discharging it to get all the energy out of the line during the compressed pulse.

B. Switching during charging time

During the charging period the power reflected from the line reaches a peak during the first time interval τ. We therefore make the iris reflection coefficient equal zero at the beginning. After the first time interval τ we switch the iris so that the reflection coefficient has a value R_0. Assuming a resonant line and flipping the phase according to Eq. (5), the output pulse expression takes the form

$$V_{\text{out}} = \{\frac{1-(R_0 p)^{n-2}}{1-R_0 p}(1-R_0^2)p + (1-R_0^2)^{1/2}\,p(R_0 p)^{n-2} + R_0\}V_{\text{in}} \;. \quad (7)$$

The choice of the value of R_0 is such that V_{out} is maximized.

C. Discharging By Active Switching

CASE1: *Discharging After The Last Time Bin*

To discharge the line, the input signal can be kept at a constant level during the time interval $0 \le t < n\tau$ but switching the iris reflection coefficient to zero so that all the energy stored in the line is dumped out. In this case

$$V_{\text{out}} = \frac{1-(R_0 p)^n}{1-R_0 p}(1-R_0^2)^{1/2}\,pV_{\text{in}}. \quad (8)$$

CASE2: *Switching Just Before The Last Time Bin*

The ingenious idea of reversing the phase, together with changing the iris reflection coefficient, can be utilized to reduce the burden on the switch. In this case, all the energy can still be dumped out of the line, but the iris reflection coefficient need not be reduced completely to zero. During the discharge interval, the new iris reflection coefficient can be shwn to be

$$R_d = \cos\left[\tan^{-1}\left(\frac{1-(R_0 p)^{n-1}}{1-R_0 p}(1-R_0^2)^{1/2}\,p\right)\right]. \quad (9)$$

This new reflection coefficient is greater than zero, so the switch need only change the iris between R_0 and R_d. The output reduces to

$$V_{\text{out}} = R_d\left[1+\left(\frac{1-(R_0 p)^{n-1}}{1-R_0 p}\right)^2(1-R_0^2)p^2\right]V_{\text{in}}. \quad (10)$$

The compressed pulse takes place in the interval $(n-1)\tau \le t < n\tau$. The optimum value of R_0 is such that it fills the system with maximum possible amount of energy in the time interval $(n-1)\tau$ instead of $n\tau$ as in CASE 1. Also, unlike CASE 1, the incident power during this interval will not be coupled to the line nor suffer from a round trip loss; therefore, in CASE 2, the system has a higher efficiency.

D. Comparison

Table 1 compares the different types of pulse compression systems. It also gives the optimum system parameters for each compression ratio C_r defined here as the total time interval divided by the duration of the compressed pulse, n. The efficiency of the system η is defined as the energy in the compressed pulse divided by the total incident energy; namely,

$$\eta = \frac{1}{C_r}\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right)^2 . \quad (11)$$

In these calculations we assume a lossless system, $p = 1$.

At small values of C_r, switching the iris just after the first time bin is the most efficient solution. When $C_r \ge 5$, switching the iris just before the last time bin, while reversing the phase by 180°, is more efficient. At high compression ratios, the last time bin does not contribute much; hence, switching the iris after the last time bin is almost equivalent to switching it just before the last time bin. For applications that require one pulse compression system or several pulse compression systems with no phase synchronization, switching after the last time bin may be advantageous because it can use an oscillator as the primary rf source instead of an amplifier or a phase locked oscillator.

	SLED II		Switching during charging time		Discharging just before the last timebin		
C_r	η (%)	R_0	η (%)	R_0	η (%) .	R_0	R_d
2	78.1	0.5	100	0.707	100	0.0	0.707
4	86.0	0.607	92.6	0.658	87.0	0.646	0.536
6	74.6	0.685	78.1	0.714	84.9	0.775	0.443
8	64.4	0.733	66.5	0.754	84.0	0.835	0.386
10	56.2	0.767	57.7	0.783	83.4	0.869	0.346
16	40.6	0.828	41.2	0.837	82.7	0.920	0.275
32	23.3	0.893	23.4	0.897	82.0	0.960	0.195
64	12.6	0.936	12.7	0.938	81.7	0.980	0.138
128	6.6	0.962	6.6	0.963	81.6	0.990	0.099

Table 1. Comparison between different methods of single event switching pulse compression systems.

E. Effect of losses

As the compression ratio increases, the stored energy spends more time in the storage line and the finite quality factor of the line affects the efficiency. Figure 2 shows the effect of losses for different compression ratios. The round-trip line losses, plus reflection losses at the end of the line and reflection losses at the active iris, is defined as

$$\text{Round Trip Power Losses} = 1 - p^2. \quad (12)$$

In Fig. 2, for a given C_r the method used to switch the iris is the optimum one for that particular C_r.

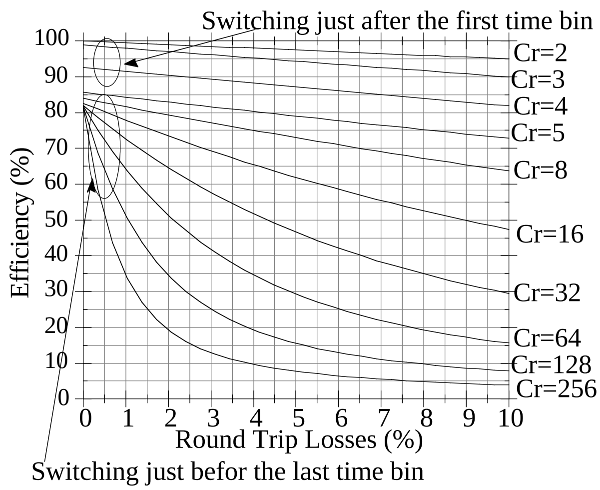

Figure 2. Effect of line and switching iris losses on compression efficiency for a one-time-switched, resonant delay line

III. THEORY OF TWICE-SWITCHED RESONANT DELAY LINE

If an iris changing its S-matrix parameters can be realized twice during the time period of charging and discharging the resonant line, a near perfect pulse compression system can be achieved. To see this, the system starts with an iris that has a zero reflection coefficient. After the first time bin, the iris reflection coefficient changes to R_0;. To discharge the line, the iris reflection coefficient is changed from R_0 to R_d just before the final time bin, while reversing the phase according to Eq.(5); optimum R_d takes the form

$$R_d = \cos\left[\tan^{-1}\left(\frac{1-(R_0 p)^{n-2}}{1-R_0 p}(1-R_0^2)^{1/2} p + p(R_0 p)^{n-2}\right)\right] \quad (13)$$

The output now has the following form

$$\frac{V_{\text{out}}}{V_{\text{in}}} = R_d\left[1+\left(\frac{1-(R_0 p)^{n-2}}{1-R_0 p}(1-R_0^2)^{1/2} p + p(R_0 p)^{n-2}\right)^2\right]. \quad (14)$$

Table 2 shows the optimum system parameters and the efficiency for different compression ratios. The system is assumed lossless in these calculations.

C_r	R_0	R_d	η (%)
4	0.776	0.502	99.2
8	0.881	0.361	96
16	0.937	0.26	92.6
32	0.967	0.187	89.7
64	0.983	0.134	87.5
128	0.991	0.095	85.8
256	0.995	0.068	84.6

Table 2. Efficiency and optimum parameters for a twice-switched resonant delay line

IV. CONCLUSION.

We have developed the theory for a single-time-switched and a twice-switched resonant delay line pulse-compression system. Comparison between different methods of switching and the original passive SLED II pulse-compression system shows that a significant improvement in efficiency can be obtained with a single-time-switched line. Furthermore, a twice-switched line can achieve efficiencies near 100% for a relatively large compression ratio. We basically have three methodologies for switching a single-time switched resonant delay line. First, we can switch the iris that governs the quality factor of the line after the first time bin; this is suitable for compression ratios less than 5. For compression ratios greater than 5, the iris should be switched just before the last time bin. At the same time, the phase of the input during the last time bin should change by 180°. For compression ratios greater than 16, switching the line after the last time bin is almost equivalent to switching the line just before the last time bin. If the application does not require control over the phase of the output, an oscillator can be used (instead of an amplifier or a phase locked oscillator) while switching after the last time bin. In all cases, losses will reduce the system efficiency greatly, especially at high compression ratios. Unlike SLED II, the gain is not limited to 9. At high compression ratios, in order to make use of the high gain provided by switching the line, a superconducting structure may be required.

V. ACKNOWLEDGMENT

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VI. REFERENCES

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