Switching speed effect of phase shift keying in SLED for generating high power microwaves

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Abstract: SLAC energy doubler (SLED) type radio-frequency pulse compressors are widely used in large-scale particle accelerators for converting long-duration moderate-power input pulses into short-duration high-power output pulses. Phase shift keying (PSK) is one of the key components in SLED pulse compression systems. Performance of the PSK will influence the output characteristics of the SLED, such as the rise-time of the output pulse, maximal peak power gain, and energy efficiency. In this paper, a high power microwave source based on power combining and pulse compression of conventional klystrons is introduced. The effects of nonideal PSK with slow switching speed and PSK without power output during the switching process are investigated, and the experimental results with nonideal PSK agree well with the analytical results.

Keywords: SLED, RF pulse compressor, phase shift keying, high power microwave

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1 Introduction

High power microwaves (HPM) have been attracting increasing attention due to their applications in radar, communications, heating in fusion, directed energy and microwave undulators [1]. Backward wave oscillators (BWO), magnetically insulated line oscillators (MILO) and virtual cathode oscillators (VCO) are common HPM generators, but although the peak power of these devices has achieved multi-gigawatts with pulse widths of tens of nanoseconds, the total energy efficiency of these HPM systems is not high [2].

With the development of particle accelerator technologies, the peak power of conventional klystrons has reached hundreds of megawatts with multi-microsecond pulse widths. RF systems based on power combining and pulse compression of moderate-power klystrons are widely used in large-scale accelerators [3]. This technique can also be used for generating HPM; this type of HPM source can realize long-term and stable operation with high repetition frequency, and has significant advantages in energy efficiency, pulse width and waveform stability compared with the HPM generators introduced above.

SLAC energy doubler (SLED) type pulse compressor systems are often chosen for their simple and compact structure, and the convenient way of energy extraction through phase shift keying (PSK) at the low power section [4]. When SLED is used for generating HPM, more attention needs to be paid to the rise time, the peak power of the output pulse and the energy efficiency than the flat pulse needed in accelerators. The performance of the PSK will influence the output characteristics of the SLED; the PSK switching phase and time jitter effects have been studied in Ref. [5] and will not be considered in this paper. The following analysis will focus on the switching speed effect of the PSK on the rise time, peak power gain and energy efficiency.

2 Theory

2.1 SLED theory with ideal PSK

Conventional SLED-type compressors contain a 3 dB coupler and two identical high Q storage cavities, as shown in Fig. 1. When the phase of the input pulse is reversed 180°, the energy stored in the cavities is discharged, the emitted field from the cavities and the reflected field are added at the output port of 3 dB coupler and then form the compressed high power pulse [6].

By the law of energy conservation and the relations between electric field and power in a waveguide, the output field of the SLED can be solved by this equation [7]:

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$$E_{\mathrm{in}}^2=E_{\mathrm{out}}^2+\frac{1}{\beta}E_{\mathrm{e}}^2+\frac{2Q_0}{\omega\beta}E_{\mathrm{e}}\frac{\mathrm{d}E_{\mathrm{e}}}{\mathrm{d}t}, \tag{1}$$

where β is the coupling coefficient and Q_0 is the unloaded quality factor of the storage cavities. Assuming the reflection coefficient between the waveguide and the storage cavities is $\Gamma=-1$, then Eq. (1) can be expressed as:

$$\tau_{\mathrm{c}}\frac{\mathrm{d}E_{\mathrm{e}}}{\mathrm{d}t}+E_{\mathrm{e}}=\alpha E_{\mathrm{in}}, \tag{2}$$

where $\tau_{\mathrm{c}}=2Q_0/\omega(1+\beta)$ is the time constant of the storage cavity and $\alpha=2\beta(1+\beta)$.

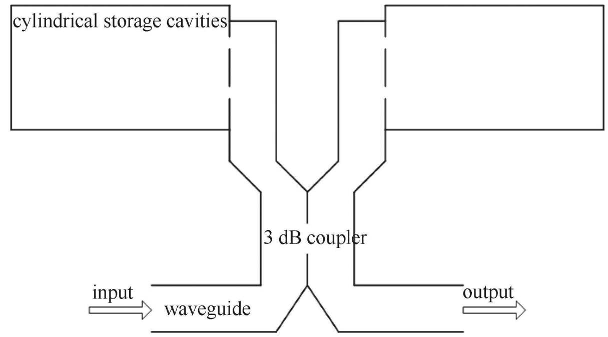

Fig. 1. Schematic of the SLED type pulse compressor.

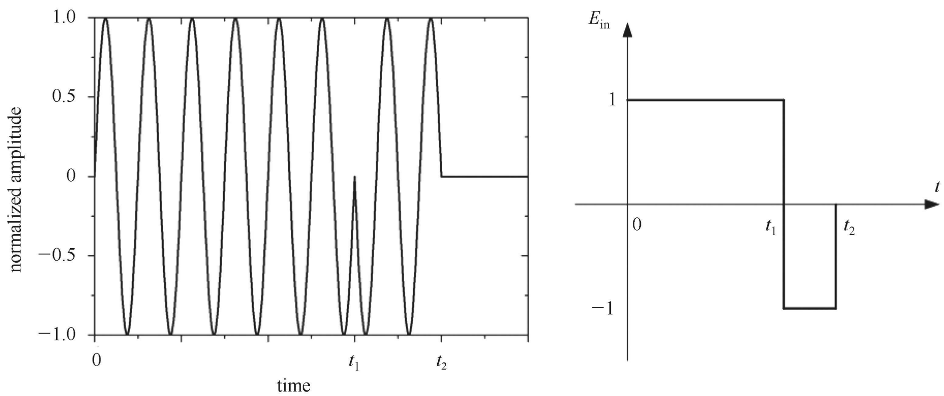

Fig. 2. Schematic of the input field with ideal PSK.

In the ideal case, the phase of the input pulse changes instantly when the PSK acts at time t_1, as shown in Fig. 2(a), and the normalized input field in the waveguide is shown in Fig. 2(b).

The normalized input field can be expressed as:

$$E_{\mathrm{in}}(t)=\begin{cases}1, & 0\leqslant t<t_1\\ -1, & t_1\leqslant t<t_2\\ 0. & t_2<t\\ . \end{cases} \tag{3}$$

At time instant $t=0$, there is no emitted field from the cavity as $E_{\mathrm{e}}=0$, and the solution of Eq. (2) is:

$$E_{\mathrm{e}}(t)=\begin{cases}\alpha\left(1-\mathrm{e}^{-t/\tau_{\mathrm{c}}}\right), & 0\leqslant t<t_1\\ \alpha\left[\left(2-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}\right)\mathrm{e}^{-(t-t_1)/\tau_{\mathrm{c}}}-1\right], & t_1\leqslant t<t_2\\ \alpha\left[\left(2-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}\right)\mathrm{e}^{-(t_2-t_1)/\tau_{\mathrm{c}}}-1\right]\mathrm{e}^{-(t-t_2)/\tau_{\mathrm{c}}}. & t_2\leqslant t\end{cases} \tag{4}$$

Then, the normalized output field of the SLED is:

$$E_{\mathrm{out}}(t)=\begin{cases}\alpha\left(1-\mathrm{e}^{-t/\tau_{\mathrm{c}}}\right)-1, & 0\leqslant t<t_1\\ \alpha\left[\left(2-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}\right)\mathrm{e}^{-(t-t_1)/\tau_{\mathrm{c}}}-1\right]+1, & t_1\leqslant t<t_2\\ \alpha\left[\left(2-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}\right)\mathrm{e}^{-(t_2-t_1)/\tau_{\mathrm{c}}}-1\right]\mathrm{e}^{-(t-t_2)/\tau_{\mathrm{c}}}. & t_2\leqslant t\end{cases} \tag{5}$$

Assuming $Q_0=10^5$, $\beta=5$ at frequency 2856 MHz, the input pulse width is 4 μs and the phase is reversed in the last 1 μs, then the normalized field of the SLED is as shown in Fig. 3. The maximal peak power gain is about 5.5 at the time instant t_1 when the phase is reversed and then decays exponentially. The energy efficiency of the SLED in this ideal case is about 71.7%, as given by Equation (6).

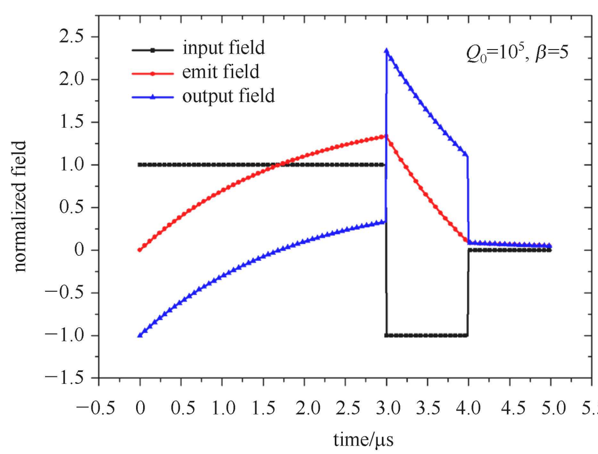

Fig. 3. (color online) Normalized field of SLED with ideal PSK.

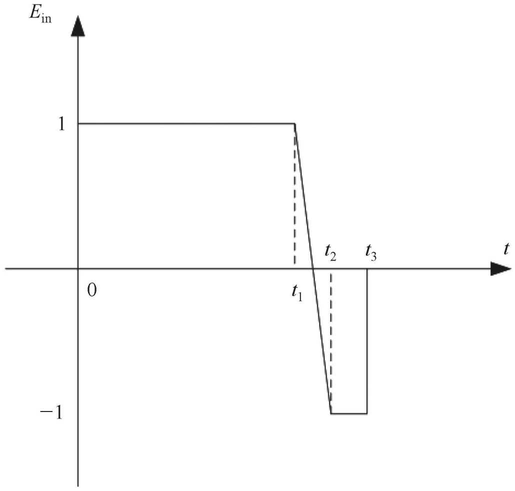

Fig. 4. Schematic of the normalized input field with slow speed PSK.

$$\eta = \frac{\int_{t_1}^{t_2} E_{\mathrm{out}}^2(t)\mathrm{d}t}{\int_0^{t_2} E_{\mathrm{in}}^2(t)\mathrm{d}t} = (1-\alpha)^2\left(1-\frac{t_1}{t_2}\right) + \frac{\alpha\tau_{\mathrm{c}}}{t_2}\left(2-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}\right)\left(\mathrm{e}^{-(t_2-t_1)/\tau_{\mathrm{c}}}-1\right) \times\left[2(\alpha-1)-\frac{\alpha}{2}\left(2-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}\right)\left(\mathrm{e}^{-(t_2-t_1)}/\tau_{\mathrm{c}}+1\right)\right]. \quad (6)$$

2.2 SLED theory with nonideal PSK

The switching speed of PSK will influence the performance of the SLED. Actually, PSK in communication and radar is usually an electrically controlled phase shifter. The phase cannot be changed instantly, as it is limited by the response time of the device. Test results show that the phase shifting process of general PSK takes some time and may even stop power output during the process.

PSK with slow switching speed will lead to variation of the input field during the phase shifting process. Assuming the phase begins to change at time t_1 and is reversed at time t_2, the normalized input field in the waveguide is as shown in Fig. 4.

The normalized input field in this case can be expressed as:

$$E_{\mathrm{in}}(t)=\begin{cases} 1, & 0\leqslant t<t_1 \\ \dfrac{-2t}{t_2-t_1}+\dfrac{t_2+t_1}{t_2-t_1}, & t_1\leqslant t<t_2 \\ -1, & t_2\leqslant t<t_3 \\ 0. & t_3\leqslant t \end{cases} \quad (7)$$

The emitted field from the cavity and the output field can be given as:

$$E_{\mathrm{e}}(t)=\begin{cases} \alpha\left(1-\mathrm{e}^{-t/\tau_{\mathrm{c}}}\right), & 0\leqslant t<t_1 \\ \alpha\left[1-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}+\dfrac{2\tau_{\mathrm{c}}+t_2+t_1}{t_2-t_1}-\dfrac{2t}{t_2-t_1}-\left(1+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}\right)\mathrm{e}^{-(t-t_1)/\tau_{\mathrm{c}}}\right], & t_1\leqslant t<t_2 \\ \alpha\left\{\left[1-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}-\left(1+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}\right)\mathrm{e}^{-(t_2-t_1)/\tau_{\mathrm{c}}}\right]\mathrm{e}^{-(t-t_2)/\tau_{\mathrm{c}}}-1\right\}, & t_2\leqslant t<t_3 \\ \alpha\left\{\left[1-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}-\left(1+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}\right)\mathrm{e}^{-(t_2-t_1)/\tau_{\mathrm{c}}}\right]\ \mathrm{e}^{-(t_3-t_2)/\tau_{\mathrm{c}}}-1\right\}\mathrm{e}^{-(t-t_3)/\tau_{\mathrm{c}}}, & t_3\leqslant t \end{cases} \quad (8)$$

$$E_{\mathrm{out}}(t)=\begin{cases} \alpha\left(1-\mathrm{e}^{-t/\tau_{\mathrm{c}}}\right)-1, & 0\leqslant t<t_1 \\ \alpha\left[1-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}+\dfrac{2\tau_{\mathrm{c}}+t_2+t_1}{t_2-t_1}-\dfrac{2t}{t_2-t_1}-\left(1+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}\right)\mathrm{e}^{-(t-t_1)/\tau_{\mathrm{c}}}\right]+\dfrac{2t}{t_2-t_1}-\dfrac{t_2+t_1}{t_2-t_1}, & t_1\leqslant t<t_2 \\ \alpha\left\{\left[1-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}-\left(1+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}\right)\mathrm{e}^{-(t_2-t_1)/\tau_{\mathrm{c}}}\right]\mathrm{e}^{-(t-t_2)/\tau_{\mathrm{c}}}-1\right\}+1, & t_2\leqslant t<t_3 \\ \alpha\left\{\left[1-\mathrm{e}^{-t_1/\tau_{\mathrm{c}}}+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}-\left(1+\dfrac{2\tau_{\mathrm{c}}}{t_2-t_1}\right)\mathrm{e}^{-(t_2-t_1)/\tau_{\mathrm{c}}}\right]\mathrm{e}^{-(t_3-t_2)/\tau_{\mathrm{c}}}-1\right\}\mathrm{e}^{-(t-t_3/\tau_{\mathrm{c}}}. & t_3\leqslant t \end{cases} \quad (9)$$

Figure 5 shows the normalized output field with different switching speed of PSK. The duration of the phase shifting process is expressed as $\Delta t = t_2 - t_1$. The switching speed has almost no effect on the peak power gain and the maximal peak power is still achieved at the instant of phase reversal. Longer Δt will lead to a slower rise time of the output pulse; when Δt is 200 ns, the energy efficiency is about 78.0%.

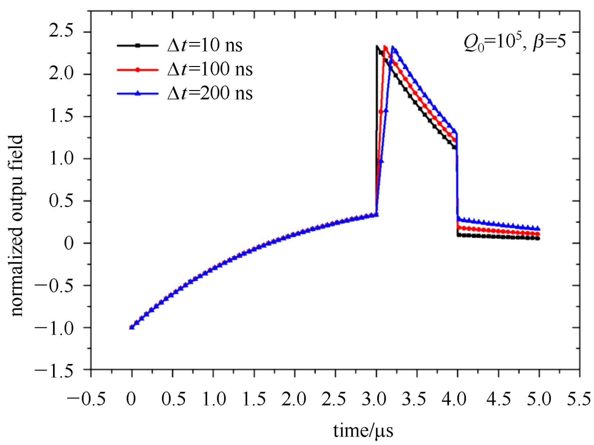

Fig. 5. (color online) Normalized output field of SLED using PSK with different switching speeds.

Another nonideal PSK which we have tested is that without power output during the phase shifting process; Fig. 6 shows the normalized input field in the waveguide with this PSK.

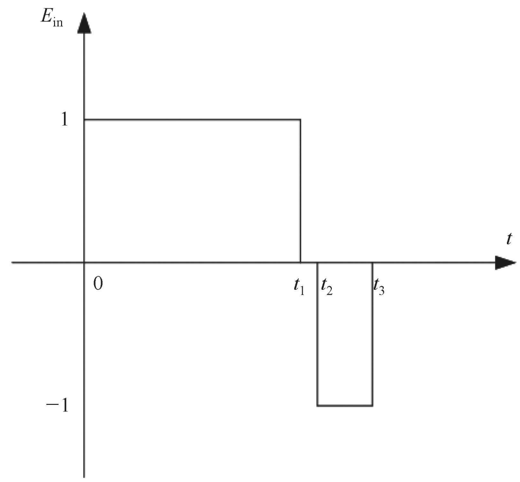

Fig. 6. Schematic of normalized input field with PSK without power output during the phase shifting process.

The normalized input field in this case can be expressed as:

$$E_{\text{in}}(t)=\begin{cases}1, & 0\leqslant t<t_1\\ 0, & t_1\leqslant t<t_2\\ -1, & t_2\leqslant t<t_3\\ 0. & t_3\leqslant t\\ . \end{cases} \tag{10}$$

The emitted field from the cavity and the output field can be given as:

$$E_{\text{e}}(t)=\begin{cases}\alpha\left(1-\text{e}^{-t/\tau_\text{c}}\right), & 0\leqslant t<t_1\\ \alpha\left(1-\text{e}^{-t_1/\tau_\text{c}}\right)\text{e}^{-(t-t_1)/\tau_\text{c}}, & t_1\leqslant t<t_2\\ \alpha\left\{\left[1+\left(1-\text{e}^{-t_1/\tau_\text{c}}\right)\text{e}^{-(t_2-t_1)/\tau_\text{c}}\right]\text{e}^{-(t-t_2)/\tau_\text{c}}-1\right\}, & t_2\leqslant t<t_3\\ \alpha\left\{\left[1+(1-\text{e}^{-t_1/\tau_\text{c}})\text{e}^{-(t_2-t_1)/\tau_\text{c}}\right]\text{e}^{-(t_3-t_2)/\tau_\text{c}}-1\right\}\text{e}^{-(t-t_3)/\tau_\text{c}}, & t_3\leqslant t\end{cases} \tag{11}$$

$$E_{\text{out}}(t)=\begin{cases}\alpha\left(1-\text{e}^{-t/\tau_\text{c}}\right)-1, & 0\leqslant t<t_1\\ \alpha\left(1-\text{e}^{-t_1/\tau_\text{c}}\right)\text{e}^{-(t-t_1)/\tau_\text{c}}, & t_1\leqslant t<t_2\\ \alpha\left\{\left[1+\left(1-\text{e}^{-t_1/\tau_\text{c}}\right)\text{e}^{-(t_2-t_1)/\tau_\text{c}}\right]\text{e}^{-(t-t_2)/\tau_\text{c}}-1\right\}+1, & t_2\leqslant t<t_3\\ \alpha\left\{\left[\left(1+\left(1-\text{e}^{-t_1/\tau_\text{c}}\right)\text{e}^{-(t_2-t_1)/\tau_\text{c}}\right)\text{e}^{-(t_3-t_2)/\tau_\text{c}}\right]-1\right\}\text{e}^{-(t-t_3)/\tau_\text{c}}. & t_3\leqslant t\end{cases} \tag{12}$$

Figure 7 shows the normalized field of the SLED using PSK with $\Delta t = 200$ ns. PSK without power output during the phase shifting process will lead to the front edge of the output pulse cutting off and the maximal power gain reducing. The maximal peak power gain is about 4.8 at the time instant t_2, and the energy efficiency is about 68.3%.

3 Experiments

In the experiments with power combining and pulse compression of conventional klystrons, a PSK module is integrated in the frequency synthesizer that was used. Test results indicate that there is about 200 ns without power output during the phase shifting process. Figure 8 shows the envelope waveform of the input pulse (CH3) and the output pulse (CH4); the peak power gain is about 4.7, the front edge of the output pulse was cut off, and the waveform of the output pulse after the input pulse was finished showed the energy stored in the cavities was not discharged completely.

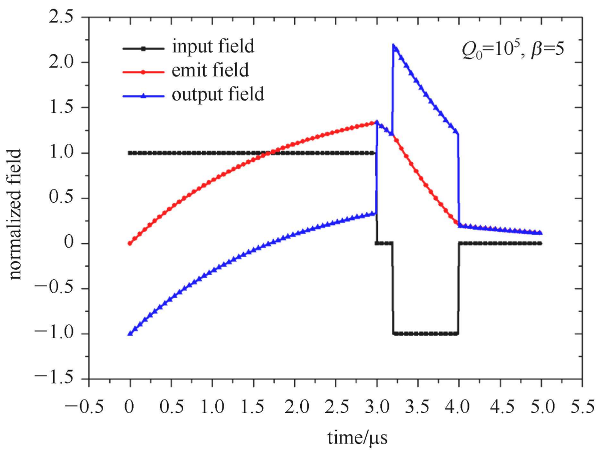

Fig. 7. (color online) Normalized field of SLED using PSK without power output during the phase shifting process.

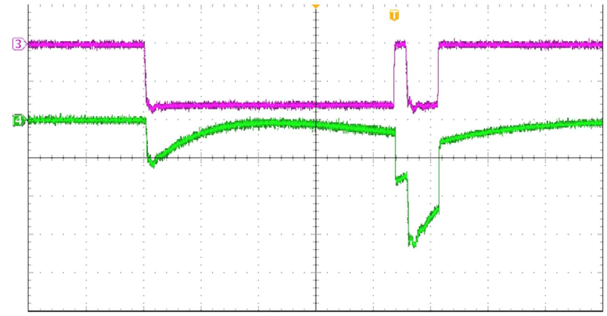

Fig. 8. (color online) Test waveform of SLED with nonideal PSK.

4 Conclusions

The switching speed effect of the PSK in a SLED for generating HPM was studied in this paper. PSK with slow switching speed has almost no effect on the peak power gain, but longer phase-shifting time leads to a slower rise time of the output pulse. PSK without power output during the phase-shifting process will lead to the front edge of the output pulse cutting off and the maximal power gain reducing. In order to generate HPM pulses with high peak power and fast rise-time, a PSK with switching speed less than 20 ns will be designed and fabricated for our experiments.

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