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# Birefringent Pulse Shaper Using Non-identical Crystals

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**Summary:** We present a new simple method to synthesize a temporal pulse shaper using non-identical birefringent crystals. The shaper configuration consists of  $N$  crystal with appropriate length and orientation placed between a polarizer and an analyzer. The Opto-geometrical shaper parameters are achieved by an optimization algorithm. This shaper is capable of generating several desired output pulse profiles with high efficiency and fidelity in both picosecond and femtosecond regimes.

**Keywords:** Birefringent pulse shaper, Laser pulse shaping, Non-identical birefringent crystals.

## 1. Introduction

Various birefringent shapers have been reported to generate desired pulse profiles, such as saw-tooth, parabolic, or flat-top pulses [1,2]. Those shapers are required in wide different fields, for instance, wavelength conversion based on self-phase modulation using a saw-tooth pulse that is more efficient than a Gaussian pulse, also, by applying parabolic pulse train as pump signal to create nonlinear time-lens [3,4]. Recently, we have demonstrated a technique to synthesize birefringent pulse shaper based on the resolution of a nonlinear system deduced from Jones matrix formalism in the time domain. The shaper consists of  $N$  identical crystals, generating  $N+1$  sub-pulses to create interference at the output polarizer to obtain the target output profile [5]. Unfortunately, this technique has two major drawbacks. Firstly, the large number of crystals complicates the optical setup and likely leads to errors in the orientation angles of the shaper's crystals. Secondly, the temporal equidistance between the sub-pulses resulting from the identical length of the crystals restricts the degree of freedom in the synthesis procedure.

This paper reports a novel method to synthesize a birefringent shaper based on non-identical crystals. The shaper generates  $2^N$  sub-pulses to produce any temporal pulse shapes, which is achieved by optimizing the amplitude of each sub-pulse and the specific time delay between any two successive pulses. This technique will overcome the disadvantages aforementioned in our previous work with only three crystals.

## 2. Synthesis procedure

In the general case of  $N$ -stages non-identical birefringent crystals (BC), and relying on the Jones matrix formalism, the polarized output electric field component  $A_{out}$  along the transmission axis of the analyzer can be described as,

$$\begin{pmatrix} A_{out} \\ 0 \end{pmatrix} = P_A R(\theta_p) \{ R(-\theta_N) R(\eta_N) R(\theta_N) \} \dots \{ R(-\theta_1) R(\eta_1) R(\theta_1) \} P_x \begin{pmatrix} A_{in} \\ 0 \end{pmatrix} \quad (1)$$

Here,  $P_x = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$  and  $P_A = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$  are the Jones matrix of the polarizer and analyzer, respectively,

$$R(\eta_i) = \begin{pmatrix} e^{j\eta_i/2} & 0 \\ 0 & e^{-j\eta_i/2} \end{pmatrix},$$

is the birefringent matrix of the  $i^{th}$  stage with  $\eta_i = \omega T_i$  denotes to the phase delay and  $\omega$  is the pulsation.

$$R(\varphi_i) = \begin{pmatrix} \cos \theta_i & \sin \theta_i \\ -\sin \theta_i & \cos \theta_i \end{pmatrix},$$

is the rotation matrix, whose absolute angle is  $\theta_i$ .

For simplicity, we rewrite Eq. (1) in terms of the relative angles  $\varphi_i$  instead of dealing with the absolute angles  $\theta_i$ , note that,  $\varphi_i = \theta_i - \theta_{i-1}$  and  $\varphi_p = \theta_p - \theta_N$ .

Eq. (1) become,

$$\begin{pmatrix} A_{out} \\ 0 \end{pmatrix} = P_A \{ R(\varphi_p) R(\eta_N) \} \{ R(\varphi_N) R(\eta_{N-1}) \} \dots \{ R(\varphi_2) R(\eta_1) \} R(\varphi_1) \begin{pmatrix} A_{in} \\ 0 \end{pmatrix} \quad (2)$$

The general form of Eq. (2) is given as,

$$\begin{pmatrix} A_{out} \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cos \varphi_p e^{-j\eta_N} & \sin \varphi_p \\ -\sin \varphi_p e^{-j\eta_N} & \cos \varphi_p \end{pmatrix} \prod_{i=2}^N \begin{pmatrix} \cos \varphi_i e^{-j\eta_{i-1}} & \sin \varphi_i \\ -\sin \varphi_i e^{-j\eta_{i-1}} & \cos \varphi_i \end{pmatrix} \begin{pmatrix} A_m \cos \varphi_1 \\ -A_m \sin \varphi_1 \end{pmatrix} \quad (3)$$

Applying the matrix product in Eq. (3), we find an exponential series form of the output electric field,

$$\begin{aligned} A_{out} &= A_m \sum_{i=0}^k A_i e^{-j\Gamma_i} \\ &= A_m (A_0 + A_1 e^{-j\Gamma_1} + \dots + A_k e^{-j\Gamma_k}) \end{aligned} \quad (4)$$

where  $k = 2^N - 1$ ,  $A_i$  are real amplitudes depend upon the relative angles, and  $\Gamma_i$  are the new phase shifts resulting from a combination between the phase shifts introduced by each stage, which are arranged according to the order of the output sub-pulses.

Taking the inverse Fourier transform of Eq. (4), we obtain the temporal output electric field,

$$\begin{aligned} e_{out}(t) &= e_{in}(t) * \sum_{i=0}^k A_i \delta(t - \Delta T_i) \\ &= \sum_{i=0}^k A_i e_{in}(t - \Delta T_i) \end{aligned} \quad (5)$$

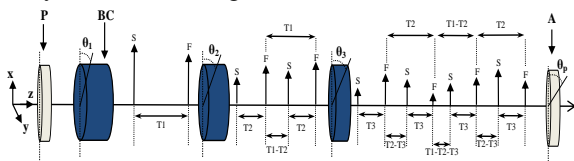
where (\*) denotes to the convolution product and  $\Delta T_i$  are the time delays between the output sub-pulses depending on each crystal's time delay, with  $\Delta T_0 = 0$ . Once the target output profile  $s(t)$  is defined,  $A_i$  and  $\Delta T_i$  can be achieved using the genetic algorithm. The error function is chosen as follows,

$$F_{err} = \left( \frac{1}{M} \sum_{n=0}^M |s(t) - e_{out}(t, A_i, \Delta T_i)|^2 \right)^{1/2} \quad (6)$$

where  $M$  is the number of time points.

### 3. Shaper design, results and discussions

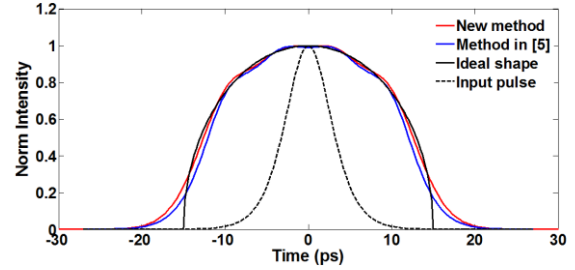
For a comparison purpose with our previous work, the schematic diagram shown in Fig. 1 fits perfectly with our case. Fig.1 illustrate the case of three stages of non-identical BC introducing different phase shifts  $\eta_1 > \eta_2 > \eta_3$ , placed between a polarizer and an analyzer. The time interval between the sub-pulses  $T_1 > T_2 > T_3$  and their amplitudes depend upon the thickness and the orientation  $\theta_1, \theta_2, \theta_3$  of each crystal. The polarizer is parallel to the x-axis while the analyzer makes an angle  $\theta_p$  with it.



**Fig. 1.** Structure of three stages of non-identical BC  
F: Impulse polarized parallel to the fast axis of the crystal  
S: Impulse polarized parallel to the slow axis of the crystal  
P: Polarizer, A: Analyzer

To prove the robustness of our new synthesis method, we chose the same temporal input pulse of our previous work [5], which has a Sech<sup>2</sup> shape with a full width at half maximum pulse duration of 6.5 ps.

Fig.2 depicts the results obtained by the new synthesis method generating a parabolic pulse profile with a 30 ps time duration. As can be seen, the output pulses match perfectly with the ideal shape. Instead of using eight stages of identical crystals as used in [5], we only use three stages of Yttrium Orthovanadate (YVO4) crystals: 16.6, 10.2 and 3.7 mm, oriented at the optimal absolute angles 135.02°, 181.19°, and 305.08°, respectively, with the absolute angle of the analyzer found to be 169.92°.



**Fig. 2.** The normalized intensity of the parabolic output pulse profile calculated by the new synthesis method

### 4. Conclusions

In this work, we have proposed a new synthesis method for temporal pulse shaping based on non-identical BC. The genetic algorithm was used to find the Opto-geometrical shaper parameters. The high effectiveness of the new method has been assessed in terms of simplicity, fidelity, and lower values of the number of stages for the parabolic target shape compared to our previous technique.

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