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The Effect of Pulse Shape on the Quality of Pulses Generated by Cross Polarized Wave Generation Technique

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Abstract:
The quality of the cross-polarized wave generation (XPW) pulses or the compression ability is studied with different apparatus settings and for two types of pulses. It has been shown that the quality of pulses thatinitially having low intensity wings can be maintained though the XPW process. Encountering nonlinear phase modulations (SPM) before the XPW process does not affect the compression of the pulses of this type. The compression ability of initially low quality pulses can be significantly enhanced in an XPW process giving that no SPM is preceding the process. If the SPM is inevitable, a compression stage between the SPM and the XPW processes can eliminated the effect of SPM on the quality of the generated pulse. Material dispersion and some intentionally introduced quadratic phase can remove the effect of SPM and keeps the high quality. However, the high pulse quality in this case is valueless because it will be accompanied by dramatic spectral narrowing.

I. INTRODUCTION

Cross-polarized wave generation (XPW) is a third order nonlinear process that depends on the anisotropy of the real part of the third order susceptibility 〖(χ〗 ^((3))) [1]. It can be easily implemented by focusing a linearly polarizedbeam of short pulses having multi-mJ energy into a crystal that has anisotropic nonlinearity and located between two crossed polarizers [2].A new beam with orthogonal polarization is generated from the highest intensity parts of the beam leaving the lower intensity parts unconverted. The unconverted part is rejected by the output polarizer. This enables a high fidelity tool for temporal contrast enhancement of short pulses [3-6]. The other inherent property of XPW pulse is the spectral broadening of the pulse originating from the third order proportionality between the fundamental and the generated pulse. In the unsaturated regime the generated signal is the cube of the input transform-limited pulse. This means that the signal is$1/\sqrt{3}$ shorter than the pump pulse.

In addition to the temporal contrast enhancement and the spectral broadening, XPW is used as a spectral filter. This feature is enabled by the third order relationship between the input and the output pulses. As the principal pulse of the pump is converted to an XPW pulse all the secondary pulses is suppressed. This temporal suppression is translated to spectral smoothing in the frequency domain [7]. However, this feature and the spectral broadening are dependent on the shape and the chirp of the input pulse [8]. The influence of the initial phase of the fundamental pulse on the performance of the XPW process is studied in several works, e.g. [8 & 9]. It has been shown that the residual phase significantly influences the performance of the XPW process with effective

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values depending on the transform limited (TL) duration of the pump pulse [8].

This workpresents a comprehensive study on the effect of the initial pump pulse shape and the apparatus of implementing the XPW generation on the performance of the process especially the quality of the resulting pulse. Since the XPW stages work usually at the front end of laser systems, the quality of the generated pulse is a quite important parameter that needs to be precisely determined. The quality of the pulse is a direct indicator on how well the pulse can be compressed and the temporal contrast of the pulse, as will be shown later. The results of the study can be used to optimize the process conditions in order to produce the highest quality pulse while its bandwidth and the generation efficiency are preserved.

II. THEORETICAL ASPECTS

When a pulse with complex amplitude A is focused into a nonlinear medium with anisotropic third order nonlinearity, a new wave is generated with polarization in the orthogonal direction. In the slowly varying amplitude approximation the complex amplitudes of the pump and the generated pulses can be estimated from [9]

$$\frac{\partial A(z,t)}{\partial z} = i\gamma_1|A|^2A - i\gamma_2(|B|^2B - A^2B^* - 2|A|^2B) + i\gamma_3(2|B|^2A - B^2A^*) \quad \text{....} \ (1)$$

$$\frac{\partial B(z,t)}{\partial z} = i\gamma_1|B|^2B - i\gamma_2(|A|^2A - B^2A^* - 2|B|^2A) + i\gamma_3(2|A|^2B - A^2B^*) \quad \text{....} \ (2)$$

where

$$\gamma_1 = \gamma_o[1 - \sigma/2\sin^2(2\beta)],$$

$$\gamma_2 = \gamma_o\sigma/4\sin(4\beta)$$

$$\gamma_3 = \gamma_o[\sigma/2\sin^2(2\beta) + (1+\sigma)/3], \quad \gamma_o = \frac{6\pi}{8\lambda n}\chi^{(3)}_{xxxx}$$

$$\sigma = \left(\chi^{(3)}_{xxxx} - \chi^{(3)}_{xyyx} - \chi^{(3)}_{xxyy}\right)/\chi^{(3)}_{xxxx}$$

B is the complex amplitude of the generated pulse, β is the angle between the polarization direction of the pump and the x axis of the crystal, χ^((3)) is the third order susceptibility of the crystal, λ is the wavelength and n is the linear refractive index of the crystal.

Equations (1) and (2) are solved by using split step method. In order to account for the dispersion in the nonlinear crystal the temporal and the spectral profiles of the pulses are propagate together. In this method the crystal is divided into thin slices where the equations (1) and (2) are solved in the temporal domain using the fourth order Runge Kutta method at the end of each slice. After that, amplitudes are transformed to the frequency domain by using Fourier transformation in order to account for the crystal dispersion. Finally, the amplitudes are transformed back to the temporal domain.

The center and the width of the temporal and spectral profiles of the pulses involved are calculated by using the following statistical method [9].

$$x_o = \frac{\int xI(x)dx}{\int I(x)dx} \quad \text{.............} \ (3)$$

$$\Delta x = \frac{\int (x-x_o)^2 I(x)dx}{\int I(x)dx} \quad \text{.........} \ (4)$$

In the case where the pulse encounter SPM before or/and after the nonlinear crystal the amplitude is obtained from solving the equation

$$\frac{\partial A(z,t)}{\partial z} + i\frac{\delta}{2}\frac{\partial^2 A(z,t)}{\partial t^2} = i\psi|A|^2 A \qquad \text{.........} \ (5)$$

where δ is the second order dispersion parameter, $\psi = n_2\omega_o\varepsilon_o/n$, n_2 is the nonlinear refractive index, and ε_o is the electric permittivity of free space.

The quality Q̆ of a laser pulse is calculated from the comparison between the pulse duration at the half maximumΔT and the standard deviation with calculated from equation (4) ΔT_{rms}[10].

$$\breve{Q} = \frac{\Delta T}{2\Delta T_{rms}} \qquad \text{..............} \ (6)$$

In order to monitor the quality of the pulse in a more sensitive way, it can be compared with the quality of the initial pulse Q_o as

$$Q = \frac{\breve{Q}}{Q_o} \qquad \text{..........} \ (7)$$

where Q will be referred to as the relative quality.

The intensity of the interacting pulses, the nonlinearity of the crystal and the length of the crystal is represented as one parameter [11].

$$S = \gamma_o|A|^2 L \ \text{............} \ (8)$$

The conversion presented this paper is performed in a 2.5 mm BaF2 crystal with holographic cut.

III. RESULTS AND DISCUSSION

A high relative quality pulse is that with perfect compression,i.e. with low energy in its wings. With the commonly used compression techniques the second and the third order phase functions can be efficiently compensated. Higher order chirps such as the fourth and the fifth order phase can be compensated by using more complicated techniques such as pulse shapers. Therefore, for high quality pulses, it is mandatory to generate pulses with as low order phase as possible.

The high quality generation can be achieved by controlling the conditions of the apparatus of the system depending on the shape of the initial pulse and the purpose of the XPW stage. If the XPW stage is used for spectral smoothening it is usually preceded by a spectral broadening stage. Commonly, this kind of stage produces spectral profile with strong modulations and fine details. This kind of pulse has relatively low quality. The quality can be then increased by employing an XPW stage.

If the fundamental pulse has a smooth temporal function, such as Gaussian or Sech2, the quality of the generated pulse stays comparable to that of the fundamental. This relation can be sustained along the nonlinear crystal with low and high intensities. Figure (1) shows an example of the relative quality of Gaussian and Sech2 functions. For this kind of pulses, the relative quality cannot be increased because the fundamental pulses have the maximum qualitydue to the low intensity wings.

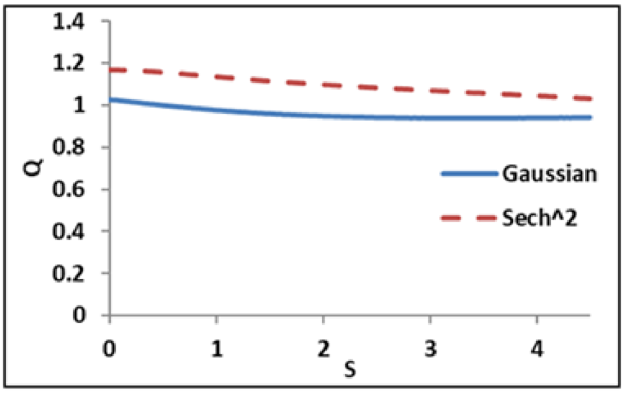

Figure (1). The relative quality of a Gaussian and a Sech2 functions as function of S factor

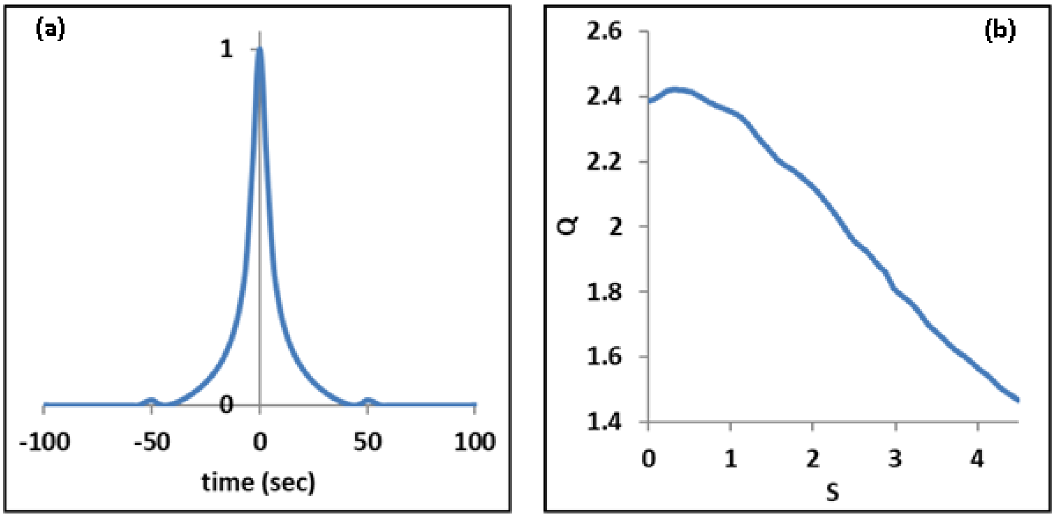

Figure (2). (a)the temporal profile of a laser pulse, (b) the relative quality of the pulse shown in the frame (a) as a function of the S factor

However, with an input pulse similar to that shown in figure (2)(a), the quality of the generated pulse is more double of the pump pulse at beginning of the crystal then drop gradually to less than 1.5, as shown in figure (2) (b). The regression of the quality as the pulse propagates though the nonlinear medium is due to the effect of self-phase modulation (SPM).

The contrast between the quality of the pulses in figures (1) and (2) shows that the quality enhancement in the XPW process depends on the initial shape of the fundamental pulse. As the energy in the wings of the pulse increases the enhancement in the quality of the pulse increases due to the suppression of the wings.

The sustainable quality of the smooth function stays sustainable even if the fundamental pulse encounters some SPM before the XPW generation crystal. The SPM can be due to the propagation of the pulse though some optics and windows or is made intentionally for spectral broadening. This state is true even at high amount of SPM. However, with pulses having high intensity wings, encountering SPM before the crystal degrades the quality even more as shown in figure (3) (a).

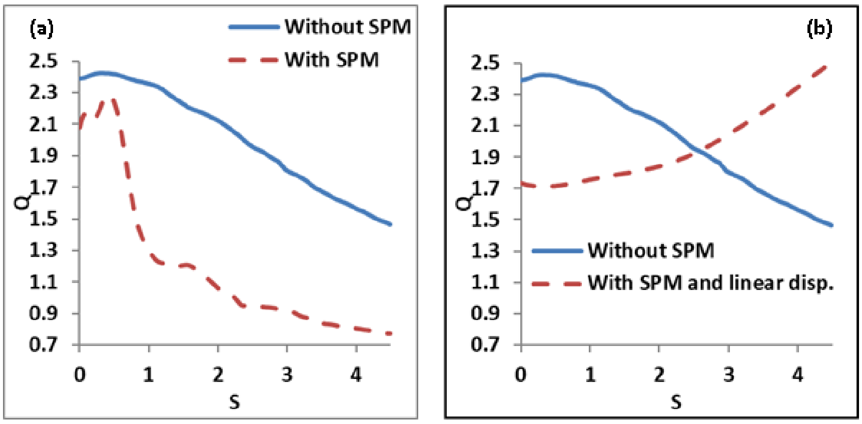

Figure (3). (a) The relative quality of the generated XPW pulses as a function of the S parameter with and without encountering SPM by the pump pulse before the XPW crystal, (b) The relative quality of the generated XPW pulses as a function of the S parameter with and without encountering SPM and linear dispersion by the pump pulse before the XPW crystal

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The effect of the SPM can be approximately canceled by installing a compression stage between the SPM and the XPW stages. The compression removes the effect of chirp on the XPW process.

The effect of SPM can also be canceled if encountering SPM is accompanied by encountering linear chirp i.e. encountering SPM in dispersive material. Interestingly, the relative quality of the XPW generated in this way can be even higher than that generated from a transform limited pulses as shown in frame (b) of figure (3). It looks like that material dispersion linearizes the SPM induced chirp.Another way to cancel the effect of SPM is by intentionally applying positive chirp to the fundamental pulse before the SPM stage. However, the applying linear chirp or that induced by material causes dramatic pulse broadening due to spectral bandwidth reduction. Therefore, the increasing quality with linear chirp is valueless.

IV. CONCLUSION

In this work a comprehensive study on the quality of the pulse generated by cross-polarized wave generation (XPW) is presented. The quality of smooth functions or low intensity wings pulses is proven to be sustainable with all the settings of the XPW apparatus. However, with high intensity wings pulses although the quality is shown to be significantly enhanced, it can be dramatically degraded due to attaining some self-phase generation (SPM) before the XPW process. The effect of SPM can be eliminated by compressing the pulse before the XPW stage. Material chirp and introduced quadratic positive phase can also cancel the effect of SPM but it comes at the cost of broadening the resulting pulse due to spectrum narrowing.

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