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Adiabatic Frequency Conversion of Ultrafast Pulses

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Abstract: A method for efficient frequency conversion of ultrafast pulses is demonstrated using an adiabatic aperiodically poled KTP crystal. We produce broadband blue pulses centered at 450 nm by upconverting 30 fs pulses in the near-IR.

1. Introduction

Nonlinear frequency conversion of intense ultrafast light sources can generate light in wavelength regions that are not easily accessible with commonly available laser systems. However, in most practical applications, there is a trade-off between bandwidth and the efficiency of the conversion [1]. In virtually all past demonstrations of frequency conversion, the efficiency of the process is dependent on maintaining small phase mismatch Δk between the interacting beams. *Adiabatic Frequency Conversion* relaxes the restriction of minimizing the phase mismatch, and instead requires Δk to be varied slowly (i.e. adiabatically) during the nonlinear interaction. This can be realized by designing a KTP crystal in which the poling period is varied spatially along the propagation axis, as illustrated schematically in Figure 1. The phase mismatch Δk between the seed (ω_1), pump (ω_2) and sum frequency ($\omega_3 = \omega_1 + \omega_2$) beams is therefore swept from $\Delta k < 0$ to $\Delta k > 0$ along the propagation axis through the crystal. In the presence of a sufficiently strong pump field ω_2, energy is efficiently and adiabatically converted from frequency ω_1 to ω_3, analogous to adiabatic population transfer in multilevel quantum systems. As is the case with other adiabatic schemes in optics [2], this technique is robust in that the conversion process is insensitive to small changes in parameters that affect the phase mismatch, such as temperature, crystal length, and input wavelength [3,4].

2. Analysis of adiabatic frequency conversion with ultrafast pulses

In order to apply these concepts to the conversion of ultrafast pulses, the dispersion properties of the nonlinear medium must also be considered. Dispersion of the pulses during propagation leads to additional temporal spreading within the crystal. Group Velocity Mismatch (GVM) causes a temporal walkoff of the incoming signal pulse ω_1 and the generated sum frequency pulse ω_3, this is typically characterized by the quasi-static interaction length $L_{QS} = \tau / GVM$, where τ is the temporal width of the seed pulse and *GVM* is the difference between the inverse group velocities of the pulses, defined as $1/v_{g_1} - 1/v_{g_3}$. We also define the adiabatic effective length, $L_{adiabatic} = \kappa / |dk/dz|$, where κ is a coupling coefficient between ω_1 and ω_3 that is dependent on the material parameters of the crystal and the field strength of the pump, and $|dk/dz|$ is the sweep rate of the phase mismatch along the propagation axis in the crystal [3,4]. The adiabatic effective length term is an adaptation of the adiabatic transition time of a general two level quantum mechanical systems [5,6], applied to the context of frequency conversion.

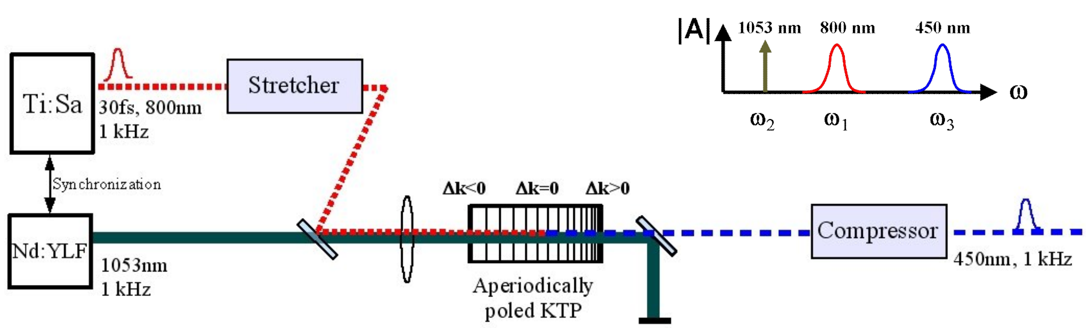

Fig. 1. Implementation of adiabatic frequency conversion of ultrafast pulses. The stretched seed pulse from a Ti:S multipass amplifier (dotted line) and a strong 1053 nm pump beam from a Q-switched Nd:YLF laser (solid line) are mixed in the adiabatic aperiodically poled KTP crystal. Under appropriate adiabatic design of the crystal, the energy of the seed beam is efficiently converted to the sum frequency beam (long dashed line).

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To overcome the problem of GVM, we require that $L_{QS} >> L_{adiabatic}$ so that the temporal walkoff between the pulses over the adiabatic interaction region is minimal. This effectively sets a limit for the minimum temporal width of the seed pulse, therefore, the seed pulse should be stretched to a duration τ_{min} which can be written as

$$\tau_{\min} \geq L_{QS} \cdot GVM >> \left| \frac{\kappa}{dk/dz} \left(\frac{1}{v_{g_1}} - \frac{1}{v_{g_3}} \right) \right| . \quad (1)$$

The group delay dispersion (as well as higher order dispersions) acquired by the sum frequency pulse ω_3 during propagation through the crystal can be compensated in a re-compression stage following the frequency conversion process.

3. Experimental results

We have implemented this scheme as shown in Figure 1. The near-IR seed pulse (typically 0.5 – 1 μJ) is generated from a 1 kHz, 1 mJ Ti:S multipass amplifier (Femtolasers GmbH). The laser spectrum is centered near 800 nm and the transform limited pulse duration is approximately 30 fs. To satisfy Eq. (1), we typically stretched this pulse in glass to 1-3 ps in duration. Stretching also reduces unwanted second harmonic generation (SHG) of the seed that would lower the efficiency of the conversion process. The output pulses of the 1 kHz Q-switched Nd:YLF pump laser were synchronized in time to the Ti:S seed pulses. The periodicity of the KTP crystal was linearly varied from 5.16 to 5.58 μm along a crystal length of 3 cm. The seed and pump beams were focused to beam diameters of 100 μm at the center of the crystal, where the pump intensity was 50 MW/cm^2. Figure 2a shows the spectrum of the blue sum frequency pulse. If compressed to the transform limit, the bandwidth of the upconverted pulse is sufficient for producing 30 fs pulses, which is the same duration as that of the unstretched seed pulse. Figure 2b shows the energy conversion efficiency of the near-IR pulse. The efficiency curve is nearly flat across the seed bandwidth (falling off only in the tails of the spectrum), indicating the robustness of the method. We have observed 11% conversion of the energy from the 800 nm seed beam into the blue. The maximum conversion efficiency achieved to date is limited only by the available pumping power in the current setup, but much higher efficiencies are achievable by increasing the pump intensity [4].

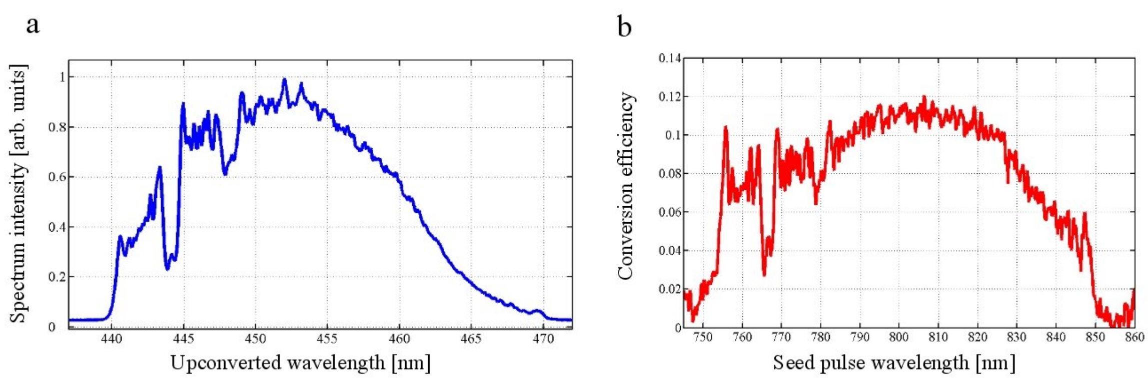

Fig. 2. (a): Frequency spectrum of the upconverted pulse. The bandwidth is sufficient for producing a 30 fs transform limited pulse. The dip near 445 nm is the result of a poling defect in the KTP crystal. (b) Efficiency of the upconversion process. The graph illustrates the fraction of seed energy that is upconverted to the blue as a function of the seed wavelength. The conversion efficiency is 11% and is largely independent of the wavelength, demonstrating the robustness of the ultrafast adiabatic SFG scheme.

This method is general and could be applied toward a wide range of ultrafast seed sources and narrowband pump sources. In particular, adiabatic frequency conversion can also be applied toward frequency downconversion. For example, with an appropriately poled crystal and the same seed and pump sources as in the current setup, we expect to efficiently generate broadband mid-IR pulses centered near 3.5 μm.

4. References

[1] M. Arbore, A. Galvanauskas, D. Harter, M. Chou, and M. Fejer, “Engineerable compression of ultrashort pulses by use of second-harmonic generation in chirped-period-poled lithium niobate” Opt. Lett. **22**, 1341 (1997).
[2] N. V. Vitanov, T. Halfmann, B. W. Shore, and K. Bergmann, "Laser-Induced Population Transfer by Adiabatic Passage Techniques", Annu. Rev. Phys. Chem. **52**, 763 (2001).
[3] H. Suchowski, D. Oron, A. Arie, Y. Silberberg, "Geometrical Representation of Sum Frequency Generation and Adiabatic Frequency Conversion", Phys. Rev. A **78**, 063821 (2008).
[4] H. Suchowski, V. Prabhudesai, D. Oron, A. Arie, Y. Silberberg, "Robust Efficient Sum Frequency Conversion", Opt. Express **17**, 12732 (2009).
[5] N. V. Vitanov, "Transition Times in the Landau-Zener Model", Phys. Rev. A., **59**, 988 (1999).
[6] K. Mullen, E. Ben-Jacob, Y. Gefen, and Z. Schuss, "Time of Zener Tunneling", Phys. Rev. Lett., **62**, 2543 (1989).