Generation of ultrafast visible and mid-IR pulses via adiabatic frequency conversion

B. D. Bruner[1], H. Suchowski[1], A. Ganany-Padowicz[2], Irit Juwiler[3], A. Arie[2] and Y. Silberberg[1]
[1]*Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel*
[2]*Department of Physical Electronics, Faculty of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel*
[3] *Dept. of Electrical and Electronics Engineering, Sami Shamoon College of Engineering, Ashdod 77245, Israel*
Email: barry.bruner@weizmann.ac.il

Abstract: A method for efficient, broadband sum and difference frequency generation of ultrafast pulses is demonstrated. Using aperiodically poled nonlinear crystals and a single step nonlinear mixing process, conversion efficiencies up to 50% are reported.
OCIS codes: (190.4223) nonlinear wave mixing; (190.7110) ultrafast nonlinear optics

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]. *Adiabatic Frequency Conversion* circumvents the trade-off associated with other frequency conversion methods, resulting in broad bandwidth conversion with very high efficiency. This method was first demonstrated for sum frequency generation (SFG) with narrowband pulses [2]. Here, we generalize the scheme and report on both sum and difference frequency generation (DFG) of broadband, ultrafast pulses.

In order to perform adiabatic frequency conversion, the phase mismatch Δk between the seed (ω_1), pump (ω_2) and SFG ($\omega_3 = \omega_1 + \omega_2$) or DFG ($\omega_3 = \omega_1 - \omega_2$) beams must be swept from $\Delta k < 0$ to $\Delta k > 0$ along the propagation axis through a nonlinear crystal. In the presence of a sufficiently strong pump field ω_2, energy is efficiently converted from frequency ω_1 to ω_3, analogous to adiabatic population transfer in two-level quantum systems. This is realized experimentally by designing periodically poled nonlinear crystals in which the poling period is varied spatially along the propagation axis. Due to this aperiodic poling of the crystal, Δk is swept from large negative to large positive values, thereby relaxing the restriction of minimizing the phase mismatch Δk between the interacting beams. As is the case with other adiabatic schemes in optics [3], this technique is particularly advantageous 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 [2].

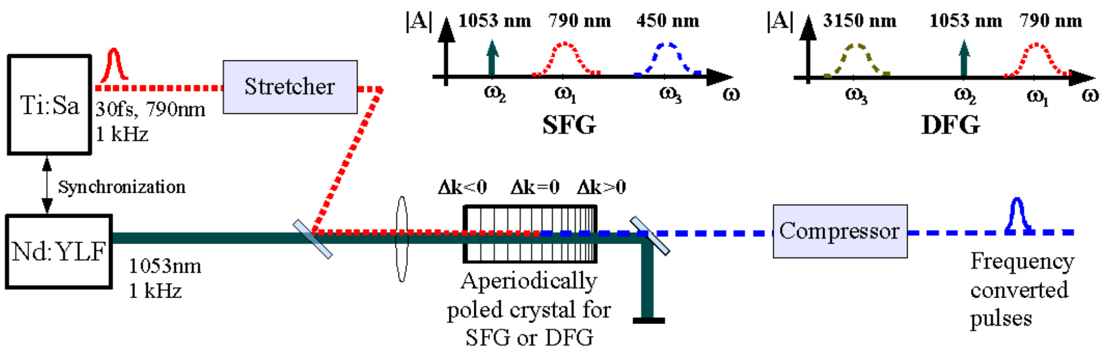

Fig. 1. Implementation of adiabatic frequency conversion of ultrafast pulses. The stretched seed pulse from a Ti:S multipass amplifier (dotted red line) and a strong 1053 nm pump beam from a Q-switched Nd:YLF laser (solid green line) are mixed in the adiabatic aperiodically poled nonlinear crystal. Depending on the adiabatic crystal design, the energy in the seed beam can be efficiently converted to either the sum frequency or difference frequency beam (long dashed blue line).

2. Frequency conversion of ultrafast pulses

In order to apply these concepts to frequency conversion of ultrafast pulses, the dispersion properties of the nonlinear medium must also be considered. It is essential to account for the Group Velocity Mismatch (GVM) of the pulses, which results in a temporal walkoff of the signal beam ω_1 from the generated sum or difference frequency beam ω_3. The GVM is defined as $1/v_{g_1} - 1/v_{g_3}$, where v_{g1} and v_{g3} are the group velocities of the seed and frequency converted pulses, respectively. The effect of GVM during a nonlinear interaction is typically

AMD6.pdf

characterized by the quasi-static interaction length $L_{QS} = \tau/GVM$, where τ is the temporal width of the seed pulse. 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. The adiabatic effective length term therefore characterizes the length over which the frequency conversion process takes place within the nonlinear crystal. It is an adaptation of the adiabatic transition time of a general two level quantum mechanical systems [4], applied to the context of frequency conversion.

To minimize the effect of GVM, we require $L_{QS} >> L_{adiabatic}$ so that the temporal walkoff between the pulses over the adiabatic interaction region is minimal. This 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 [5]:

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

3. Experimental Methods

The adiabatic frequency conversion setup is shown in Figure 1. With the exception of the nonlinear crystal, the setup used in the experiments was identical for both the SFG and DFG implementations. The pump source was a 1 kHz Q-switched Nd:YLF laser centered at 1053 nm. The pump laser pulses were synchronized to the output of a 1 mJ Ti:S multipass amplifier (Femtolasers GmbH), with its spectrum centered near 790 nm and a transform limited pulse duration of approximately 30 fs. From this Ti:S amplifier, we typically used 0.5 – 1.5 μJ of energy for the seed, and stretched these pulses in glass to a duration of 1-3 ps in order to satisfy the requirement set by Eq. (1). For SFG, we designed an aperiodically poled KTP crystal in which the periodicity was linearly varied from 5.16 to 5.58 μm along a crystal length of 3 cm. This design enables conversion of 80 nm of total bandwidth from the seed pulses. For DFG, we designed an SLT crystal in which the periodicity was linearly varied from 22.6 to 23.4 μm along a crystal length of 2 cm, which enables conversion of 20 nm of bandwidth from the near-IR seed pulses into the mid-IR. The seed and pump beams were focused to beam diameters of 100 μm at the centers of the crystals, where the pump intensity was 50 MW/cm^2 [5].

4. Results

The spectra of the frequency converted pulses and their corresponding efficiency curves are shown in Figures 2 and 3. The efficiency curves depict the fraction of seed energy that is converted as a function of seed wavelength. Although we have not yet performed the post-compression and characterization of the pulses, we have observed excellent conversion of the spectral shape and bandwidth of the seed to both the visible and mid-IR wavelength regions [5]. For the SFG pulse (Fig. 2), the spectrum is centered near 450 nm and its bandwidth is sufficient for producing 30 fs pulses if compressed to the transform limit – a pulse duration equal to that of the fully compressed seed beam. For the DFG pulse (Fig. 3), the spectrum is centered near 3150 nm and two-thirds (20 nm) of the FWHM seed bandwidth was converted to the mid-IR. This was the maximum obtainable bandwidth as per the design of the crystal. The complete seed bandwidth could be converted by designing a longer aperiodically poled crystal or by altering the spatial sweep rate of the poling period.

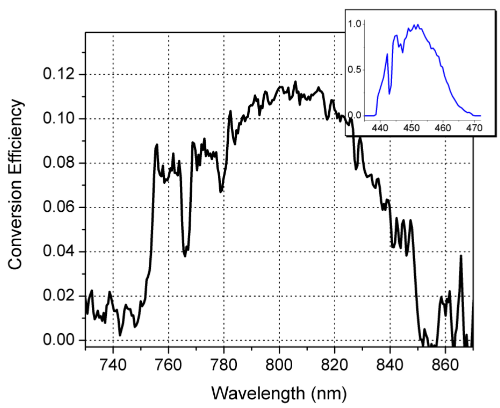

Fig. 2. Measured conversion efficiency of the seed pulse in the SFG process. Inset: normalized spectrum of the SFG pulse as a function of wavelength in nm.

AMD6.pdf

Both the DFG and SFG efficiency curves are largely flat across the seed bandwidth (falling off only in the tails of the spectrum), indicating the robustness of the adiabatic frequency conversion method. The conversion efficiencies reach a peak of 11% for SFG and 50 % for DFG, in good agreement with the calculated efficiencies for the nonlinear crystals and pump intensities used in the experiment. For both SFG and DFG, the efficiency was limited in large part due to the available pump power, but much larger efficiencies, even approaching 100% in principle, are achievable by a sufficient increase in the pump intensity [2].

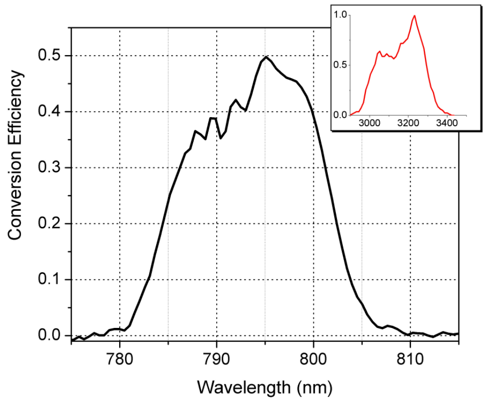

Fig. 3. Measured conversion efficiency of the seed pulse in the DFG process. Inset: normalized spectrum of the DFG pulse as a function of wavelength in nm.

5. Discussion and outlook

Another important advantage to adiabatic frequency conversion is that the spectral phase of the ultrafast pulse is preserved in the frequency converted field, provided that the undepleted pump approximation holds. This has important implications for generating shaped ultrafast pulses in wavelength regimes where direct shaping is difficult or inaccessible using currently available pulse shaping technology, particularly in the mid-IR. Additionally, adiabatic frequency conversion enables scalable conversion from the near-IR to the mid-IR with a single efficient conversion step, in contrast to existing mid-IR ultrafast pulse generation schemes that normally involve multiple frequency conversion steps.

6. 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] H. Suchowski, D. Oron, A. Arie, Y. Silberberg, "Geometrical Representation of Sum Frequency Generation and Adiabatic Frequency Conversion", Phys. Rev. A **78**, 063821 (2008); H. Suchowski, V. Prabhudesai, D. Oron, A. Arie, Y. Silberberg, "Robust Efficient Sum Frequency Conversion", Opt. Express **17**, 12732 (2009).

[3] 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).

[4] N. V. Vitanov, "Transition Times in the Landau-Zener Model", Phys. Rev. A., **59**, 988 (1999).

[5] H. Suchowski, B. D. Bruner, A. Ganany-Padowicz, I. Juwiler, A. Arie, Y. Silberberg, "Adiabatic Frequency Conversion of Ultrafast Pulses", Opt. Lett. (submitted).