Control of frequency chirp in a PPKTP optical parametric oscillator with near Fourier-limited bandwidth

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Abstract: We use nonlinear optical processes to generate narrowband light from an optical parametric oscillator, yielding significantly improved frequency stability compared with dye lasers where the chirp arises principally from population inversion. We measure chirp using optical heterodyne detection and minimise it by phase matching, producing a near Fourier-transform limited bandwidth.

Pulsed, tunable coherent light sources with high peak power and narrow optical bandwidth are needed for many high-resolution laser spectroscopy applications, notably in the vacuum ultraviolet (VUV) region for which nonlinear optical upconversion is used to generate the required wavelengths. For instance, the 2¹S ← 1¹S two-photon absorption transition of atomic helium has been measured with narrowband 120-nm VUV radiation generated by pulsed dye amplification of a cw tunable Ti:sapphire laser, followed by four-wave mixing upconversion.

However, the precision of these VUV spectroscopy studies is limited by degradation of the frequency bandwidth arising from the pulsed dye amplification processes. This is the result of both shot-to-shot fluctuations in the frequency of the dye laser pulse due, for example, to thermal lensing and dye flow inhomogeneities, as well as frequency chirp arising from the changes in the population inversion during the pulse itself.

To circumvent these bandwidth limitations, we have generated narrow linewidth radiation using nonlinear optical crystals which yield better shot-to-shot frequency stability and which by definition have no contribution to frequency chirp arising from population inversion. This approach is based on an injection-seeded, pulsed OPO/OPA system. The first stage comprises a single-longitudinal-mode (SLM) PPKTP (periodically poled KTiOPO₄) OPO injection-seeded at ~840 nm by a cw tunable diode laser (TDL), as in Fig. 1. The OPO is pumped at 532 nm by a SLM Nd:YAG laser with a long pulse duration (28 ns) to reduce the Fourier-transform-limited optical bandwidth. These experiments extend our earlier investigations of OPO frequency chirp with shorter pulse durations (~8 ns). We have also added two OPA stages to further amplify the OPO pulse with the aim of producing sufficient power for nonlinear frequency conversion into the VUV.

Fig. 1. Schematic of the TDL-seeded ring-cavity PPKTP OPO, and optical heterodyne beat-signal measurement system; M = mirror; BS = beamsplitter; PZT = piezoelectric translator; AOM = 730-MHz acousto-optic modulator.
To characterise and minimise frequency chirp effects arising from time-dependent optical phase variations during the OPO pulse, we have adapted an optical-heterodyne (OH) approach. A similar technique was used to measure optical phase properties of pulsed, tunable coherent light in high-resolution spectroscopic systems comprising a cw SLM laser pulse-amplified by dye-laser media. We take the OPO output and beat it with the AOM-shifted (by ~730 MHz) cw seed laser and measure the beat signal with a fast photodetector (Fig. 1).

The instantaneous frequency $f_{\text{inst}}$ (the time-derivative of optical phase of the OPO pulse) is extracted by Fourier-transforming the OH beats, filtering one of the AOM-shifted sidebands, and back-transforming into the time domain. Fig. 2 (lower left) shows the instantaneous frequency variation during the pulse. The resulting frequency chirp is plotted (right) as a function of the seed laser detuning from the gain peak of the free-running OPO ($\lambda_{\text{free}}$), at which wavelength the phase matching of the seed and pump lasers in the PPKTP crystal is optimal. The frequency chirp can be made to close to zero by operating at the phase matching wavelength.

![Fig. 2](image-url) (Top left) A simulated temporal profile of signal output pulse intensity exhibits rapid 'walk-off' oscillations that accompany partial seeding at higher pump powers ($R_p = 3.5$ times) above threshold. (Lower left) Simulated and experimental profiles of the instantaneous frequency $f_{\text{inst}}(t)$ agree well. (Right) Frequency chirp as a function of cw-seeded OPO signal wavelength. The dashed vertical line marks the free-running OPO centre wavelength $\lambda_{\text{free}}$.

We have simulated the performance of our OPO based on the SNLO code developed by Smith and coworkers at Sandia laboratories and compare the results with our experimental data (fig.2). These simulations confirm and help to explain various forms of dynamical behaviour (e.g., the transition from single-mode to multi-mode operation – fig. 2 left) that are observed in this OPO. We have also used OH to perform direct spectroscopic measurements of the OPO/OPA resolution using a new technique - Coherent Heterodyne-Assisted Pulsed Spectroscopy (CHAPS) which demonstrates that indeed the OPO/OPA bandwidth is very close to the Fourier transform limit.

References