Statistical Description of Capillary-Based High-Harmonic Generation

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High-harmonic generation (HHG), where the interaction of high-intensity laser light with matter generates ultrashort XUV pulses, is an attractive option for a table-top source of coherent light at nanometre wavelengths. Its efficiency can be improved by performing the HHG in a gas-filled capillary instead of the more common gas jet or cell due to improved interaction length and phase matching. However, because of the highly nonlinear interaction between pump light, neutral atoms, generated plasma, and XUV radiation in this regime, accurate computer simulations and predictions are highly complex and time consuming.

Here we present a novel approach to predicting high-harmonic spectra from a capillary-based HHG system that is approximate but is a hundred times faster to compute than explicit simulations and thus will allow for the first time to perform large parameter scans of such systems. At the centre of our approach is a statistical analysis of the highly nonlinear pump pulse propagation through the capillary. In a first step, the pump propagation is simulated using an efficient multimode generalised nonlinear Schrödinger equation (MM-GNLSE) [1]. The highly nonlinear dynamics break up the pump pulse into a train of subpulses of rapidly fluctuating intensities and temporal widths. Next, we fit a bivariate gamma distribution [2] to this set of correlated intensity-width data such that mean values, variances, skews and intensity-width covariance are reproduced; an example is shown in Fig. 1(a). Interpreting this fit as a subpulse probability distribution function then allows us to calculate the capillary high harmonic output spectrum as a weighted sum of pre-calculated single-atom HHG spectra [3] of individual pulses over a range of intensities and widths, where wavelength-dependent XUV absorption and the gas density distribution in the capillary are also taken into account. This procedure generates predictive spectra with well resolved harmonic peaks, see Fig. 1(b). We note that this spectrum is obtained as an incoherent sum over spectral contributions emitted at different positions in the capillary and thus neglects phase matching. However, we find that the predicted general envelope of the harmonics is a good match to spectra obtained via full explicit HHG simulations. Most importantly, with our approach a high-harmonic spectrum can be calculated in a matter of minutes with low computational complexity, compared to the hours of computation time required for an explicit simulation.

To reduce the complexity of the computational model further, we are also investigating the possibility of a "global" fit that will provide the parameters of the bivariate gamma distribution of the subpulses as a function of e.g. the pump pulse intensity and the gas pressure. In this case, the method would be characterised in terms of simple polynomials and datasets, providing a toolbox by which harmonic spectra could be predicted without the simulation of the MM-GNLSE and the subsequent statistical analysis of generated subpulses.

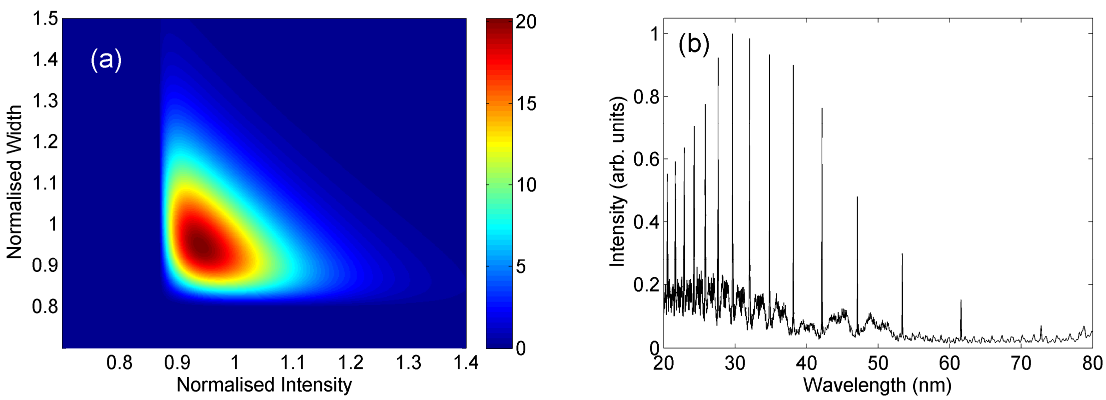

Fig. 1. (a) Bivariate gamma distribution of pump subpulse intensities and widths for an 800 mJ pump pulse at 780 nm wavelength propagating through a 7 cm long capillary filled with 100 mbar of Ar. (b) Corresponding predicted high harmonic output spectrum of the capillary as an incoherent sum of the harmonics generated by the distribution of subpulses.

References

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