Enhanced control of molecular modulation in hollow-core fibers

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For more than a decade now, broadband-guiding hollow-core photonic crystal fibers (HC-PCFs) have revolutionized the world of gas-based nonlinear photonics through their unique characteristics: low attenuation over transmission windows spanning several octaves, tight modal confinement, low light-glass overlap and pressure-tunable dispersion and nonlinearity. In particular, stimulated Raman scattering and molecular modulation processes are greatly enhanced in this type of fibres, giving rise to interesting applications such as broadband frequency conversion of arbitrary optical signals in a pure fundamental core mode, with record high efficiencies reaching 80% [1] or the complete coherent suppression of the intramodal Raman gain in a fully collinear arrangement [2]. This latter phenomenon, first predicted more than half a century ago, allows strong enhancement of processes with weaker scattering strengths, such as intermodal Raman scattering, uniquely enabling efficient emission of down-shifted Stokes signals with an adjustable spatial profile.

In this talk, we will review the different routes for achieving enhanced control over molecular modulation processes taking place inside gas-filled HC-PCFs. In particular, we will focus on the recent development of synthesized Raman nonlinear responses in mixtures of Raman-active and noble buffer gases [3]. In sharp contrast to previous reports, where the addition of a buffer gas merely caused strong dephasing to transitions involving higher-order sidebands, together with an overall reduction of the Raman gain due to additional collisions with the molecules, we will show how the opposite occurs in HC-PCFs provided the dispersion can be accurately controlled. To illustrate this, in Fig. 1(a) we plot the dimensionless exponential Raman gain factor \( G_r \) [3] for a kagomé-style HC-PCF filled with an H\(_2\)-Xe mixture, operating in the transient regime. The overall gain, as well as the pressure at which coherent gain suppression occurs (\( P_{H_2} = 18 \) bar in the pure H\(_2\) case, see Fig. 1(b)) can be both precisely adjusted by means of the buffer gas pressure.

\[ \text{Fig. 1} \text{ (a) Exponential gain factor } G_r \text{ as a function of the partial pressures of hydrogen and xenon. The gain suppression point shifts to lower H}_2 \text{ pressures with the addition of a buffer gas. (b)-(c) Experimental (symbols) and simulated (lines) energies of vibrational Stokes/anti-Stokes sidebands measured at the output of a 37-cm-long kagomé HC-PCF pumped with 1-ns pulses at 532 nm with 3.6 } \mu \text{J of energy and filled with pure hydrogen in (b) and with a gas mixture involving a fixed hydrogen pressure of } P_{H_2} = 13.5 \text{ bar in (c). The insets show the near-field mode profiles of each spectral band.} \]

Remarkably, when the nonlinear coupling between the interacting fields is strong, the gas-mixture-based system can, counterintuitively, outperform that of a pure Raman-active gas (see Fig. 1(c)). In particular, all the sidebands emerge in a pure fundamental mode and the overall anti-Stokes efficiency increases, but at a lower total gas pressure, thus mitigating against parasitic effects such as Raman back-scattering [3].

This new class of gas-based waveguide device, whose nonlinear response can be beneficially adjusted by the addition of other gases, constitutes a promising platform for efficient frequency conversion to the ultraviolet, where the number of current alternatives is very limited.

References