

Quadratic Cavity Solitons for Enhanced Optical Gas Sensing

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Abstract: We utilize the unique formation dynamics of quadratic cavity solitons for enhanced sensing, experimentally show CO₂ sensing with high sensitivity and large dynamic range, and present the promising potentials of soliton-enhanced gas sensors. © 2022 The Author(s)

Gas sensors are vital for a number of applications, including process controls, environmental monitoring, safety, and medical breath analysis. Optical gas sensors provide an economical solution which can still provide high sensitivity and reliability [1]. Extremely high sensitivity and small detection limits in optical gas sensing have been achieved through the use of cavity-enhanced methods at the cost of requiring low-loss, high-finesse resonators [2, 3]. Intracavity absorption spectroscopy (ICAS) can reduce the need for such high-finesse cavities through the introduction of a gain medium to the cavity and utilization of the nonlinear dynamics of lasers near threshold for enhanced sensing; however, constraints on the spectral availability of laser gain media as well as parasitic effects which can couple cavity modes have inhibited its broad application [4]. While optical parametric oscillators (OPOs) have been considered a promising replacement for lasers in ICAS due to their gain availability at arbitrary wavelengths [5], prior experimental attempts in the quasi-CW [6] and short-pulsed regimes [7] have remained distant from theoretical predictions due to technological challenges as well as lack of understanding of the nonlinear dynamics of pulsed OPOs. Additionally, all such optical gas sensors exhibit an unfavorable trade-off between dynamic range and sensitivity. Here, we detail a sensing mechanism based on the dynamics of the simulton regime in pulsed OPOs [8] which can provide both sensitivity enhancement and large dynamic range. Experimentally, we demonstrate sensitivities up to 3.5 mW/ppm across the range of atmospheric CO₂, and we show a path towards improvement by several orders of magnitude.

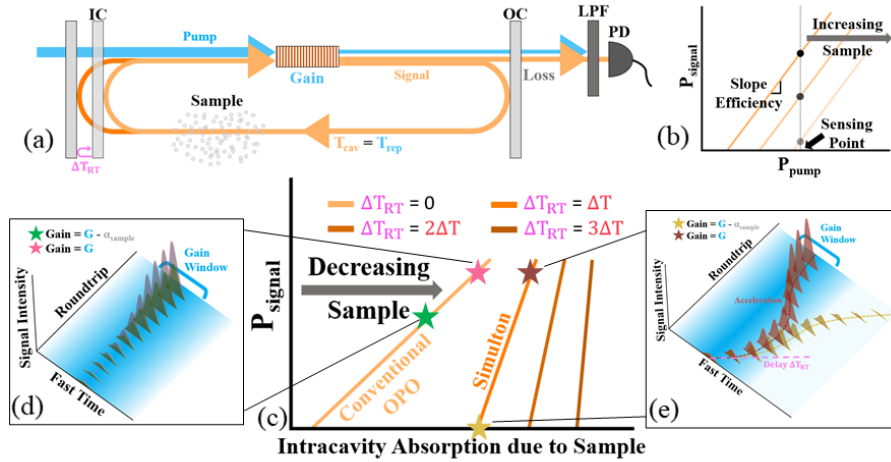


Fig. 1. Enhanced gas sensing using nonlinear dynamics associated with the formation of quadratic cavity solitons. (a) Schematic depiction of intracavity sensing in an OPO. IC, input coupler; OC, output coupler; LPF, long pass filter; PD, photodetector. (b) The sensitivity at a given sensing point is defined locally by the slope efficiency. (c) The high simulton slope efficiency near threshold ensures a higher sensitivity, which arises because the simulton must extract enough gain to accelerate and satisfy the timing condition (e), as compared to the conventional OPO (d).

The sensing mechanism is illustrated in Figure 1a. A pump pulse train with repetition period T_{rep} is sent to the cavity through an input coupler. The signal at the half-harmonic of the pump, which interacts with the gas sample each roundtrip, extracts gain from the pump through a quadratic nonlinear crystal. An output coupler keeps residual pump light from propagating in the roundtrip and allows for measurement of signal light on a photodetector. The sensitivity of the method is dependent on the slope efficiency of the signal pulse (Figure 1b),

with a higher slope efficiency near the sensing point corresponding to a greater sensitivity. The highest slope efficiencies in optical parametric oscillators have been attributed to the formation of solitons, a form of cavity soliton which consists of a co-propagating bright-dark soliton pair in the pump and signal [8]. Solitons can be attained through the addition of a delay, ΔT_{RT} , with respect to synchronous operation ($T_{cav} = T_{rep}$), as the delay balances the nonlinear acceleration experienced by the soliton in the crystal. This high slope efficiency translates to higher sensitivity for the soliton regime (Figure 1c). As compared to a conventional OPO which does not have such a timing condition (Figure 1d), the addition of a small amount of loss in the soliton case causes it to experience an insufficient acceleration to compensate the delay and thus creates a drastic change in signal power over a small range of sample concentrations (Figure 1e).

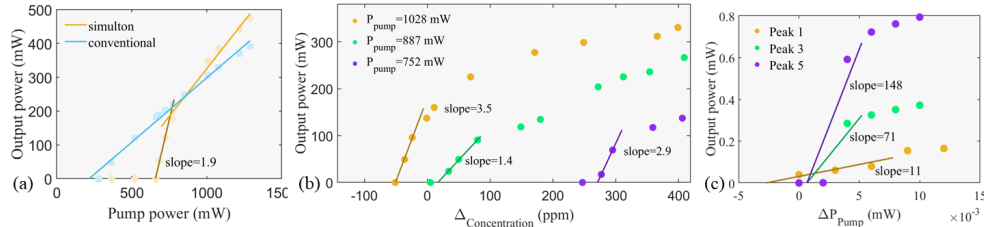


Fig. 2. Experiments and simulations of sensitivity enhancement from cavity soliton dynamics. (a) Comparison of measured conventional and soliton slope efficiencies in the 4μm OPO highlighting the large slope efficiency of the soliton near threshold. (b) CO₂ measurements showing high sensitivity for the soliton. Adjustment of the pump power enables a large dynamic range. The x-axis shows the difference in concentration from atmospheric CO₂ (415 ppm). (c) Numerical simulation illustrating improvement in slope efficiency for farther delayed soliton resonances. The x-axis shows the difference in pump power away from the peaks' respective thresholds.

We experimentally demonstrate the sensitivity enhancement provided by the soliton through measurement of CO₂ in a free-space degenerate OPO based on orientation-patterned GaP pumped at 2.09 μm, described in [9]. The signal, centered at 4.18 μm with 900 nm FWHM instantaneous bandwidth, experiences strong absorption from the CO₂ P and R branches which span 4200–4350 nm. The CO₂ level is varied through the introduction of N₂ to a purging box which surrounds the cavity. For calibration, the CO₂ concentration is monitored with a commercial CO₂ sensor. Figure 2a presents a comparison between the soliton and synchronous input-output power dependencies for the sample-free cavity and demonstrates a high slope efficiency of 190% for the soliton near threshold, which translates to a high sensitivity of 3.5 mW/ppm (Figure 2b). Additionally, we observe that a large dynamic range for the sensor can be achieved through variation of the pump power, as this change in gain results in a different threshold concentration of CO₂ above which the soliton can resonate. This contrasts traditional optical sensors, for which there is an inherent tradeoff between sensitivity and dynamic range. Furthermore, whereas one can risk saturation of the detector or sample of interest through increasing the pump power in a traditional optical gas sensor, the residual pump in the soliton sensing case can be filtered out, leaving only the signal.

Finally, we explore the theoretical limits of the proposed sensing mechanism through numerical simulations of the coupled wave equations utilizing a Fourier split-step method. Our numerical results, shown in Figure 2c, suggest over one order of magnitude improvement in slope efficiency can be achieved by moving to a larger cavity delay, with the maximum simulated slope efficiency nearing 14,800%. This indicates that moving to larger delays is advantageous for sensing if sufficient pump power is available and shows the future potential of this mechanism.

In summary, we have demonstrated how the nonlinear dynamics of quadratic cavity solitons can be utilized for enhanced sensing. We have shown a proof-of-principle experiment for CO₂ sensing in the mid-IR and presented a path towards improved performance. Our results combined with recent progress on integrated nonlinear photonics [10] enabling high-gain OPOs can pave a promising path towards next generation optical gas sensors.

References

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