HSF Interpretation of Asymmetric Sideband Generation in Strongly-Driven Rydberg Atoms

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We present a compact account of the asymmetric $-3\,\mathrm{dB}$ bandwidths of negative and positive optical sidebands generated by strongly-driven Rydberg atoms. Within standard EIT/Rydberg theory, the negative sideband (SB−) bandwidth is governed by optical coherence scales (coupling Rabi frequency Ω_C and natural linewidth Γ), whereas the positive sideband (SB+) is limited by the slow Rydberg coherence with decay rate γ_{er}. We propose a Harmonic Scale Framework (HSF) interpretation that clarifies why SB− is robust but SB+ is fragile under probe-induced back-action, without modifying the standard equations of motion.

I. INTRODUCTION AND PROBLEM

Rydberg-atom receivers combine electromagnetically induced transparency (EIT) with strong Rydberg nonlinearities to realize RF-to-optical downconversion and optical sideband readout. A persistent issue is the limited bandwidth arising from finite Rydberg-state coherence times. Recent experiments report a clear asymmetry: SB− can exceed 10 MHz, while SB+ remains near 3.5–5 MHz under optimal conditions. We ask whether a minimal scaling grounded in standard EIT theory, together with an HSF interpretation, can capture these magnitudes and their asymmetry.

II. THEORY

In standard EIT, the probe (Ω_P) and coupling (Ω_C) fields open an Autler–Townes/EIT window whose bandwidth is set by Γ and power broadening; comprehensive reviews include Fleischhauer *et al.* [1]. Rydberg-EIT bandwidths and nonlinearities scale with Rabi frequencies and decoherence rates [2]. For the sidebands generated by LO+SIG mixing, a minimal expectation is

$$\Delta f_- \sim \frac{\Omega_C^2}{\Gamma} \quad \text{(optical scale)}, \tag{1}$$

$$\Delta f_+ \sim \gamma_{er} \quad \text{(Rydberg coherence/decay scale)}. \tag{2}$$

Operational meaning of HSF. HSF here is *not* an alternative dynamics or Hamiltonian. It is an *interpretive layer* that organizes the standard theory in terms of two operational scales: (i) a *fast* optical coherence controlled by Ω_C and Γ (setting SB− via Eq. (1)), and (ii) a *slow* Rydberg-state coherence characterized by γ_{er} (setting SB+ via Eq. (2)). Increasing Ω_P acts as measurement back-action that shortens the slow coherence first.

III. DATA

We analyze the Fig. 6b subset provided to us: (i) varying Ω_C at fixed $\Omega_P = 1.66\,\mathrm{MHz}$, and (ii) varying Ω_P at fixed $\Omega_C = 18.02\,\mathrm{MHz}$. The numerical values are embedded below.

TABLE I. Fixed $\Omega_P/(2\pi) = 1.66\,\mathrm{MHz}$; varying $\Omega_C/(2\pi)$. Experimental (Exp) and paper theory (Th) $-3\,\mathrm{dB}$ bandwidths.

$\Omega_C/(2\pi)$ (MHz)	Exp. SB− (MHz)	Exp. SB+ (MHz)	Th. SB− (MHz)	Th. SB+ (MHz)
4.96	2.0	2.0	5.0	2.5
9.87	6.0	3.5	6.5	3.5
18.02	10.0	5.0	9.5	4.5

IV. CALCULATIONS

We take $\Gamma/(2\pi) = 6.07\,\mathrm{MHz}$ and fit the minimal laws to Table I:

$$\Delta f_- = A\,\frac{\Omega_C^2}{\Gamma}, \qquad \Delta f_+ \approx \gamma_{er}\ \text{(const.)}. \tag{3}$$

TABLE II. Fixed $\Omega_C/(2\pi) = 18.02\,\mathrm{MHz}$; varying $\Omega_P/(2\pi)$.

$\Omega_P/(2\pi)$ (MHz)	Exp. SB− (MHz)	Exp. SB+ (MHz)	Th. SB− / Th. SB+ (MHz)
1.66	10.0	5.0	9.5 / 4.5
4.06	10.0	3.5	9.5 / 4.5
8.05	11.0	3.5	11.0 / 5.0
16.11	10.5	2.5	3.0 / 2.0
24.16	0.6	0.5	1.2 / 1.0
28.17	0.5	0.4	0.8 / 0.7

A least-squares fit yields a single parameter $A \approx 0.204$ for SB−, while SB+ is consistent with $\gamma_{er} \approx 3.50\,\mathrm{MHz}$ at fixed Ω_P.

V. RESULTS

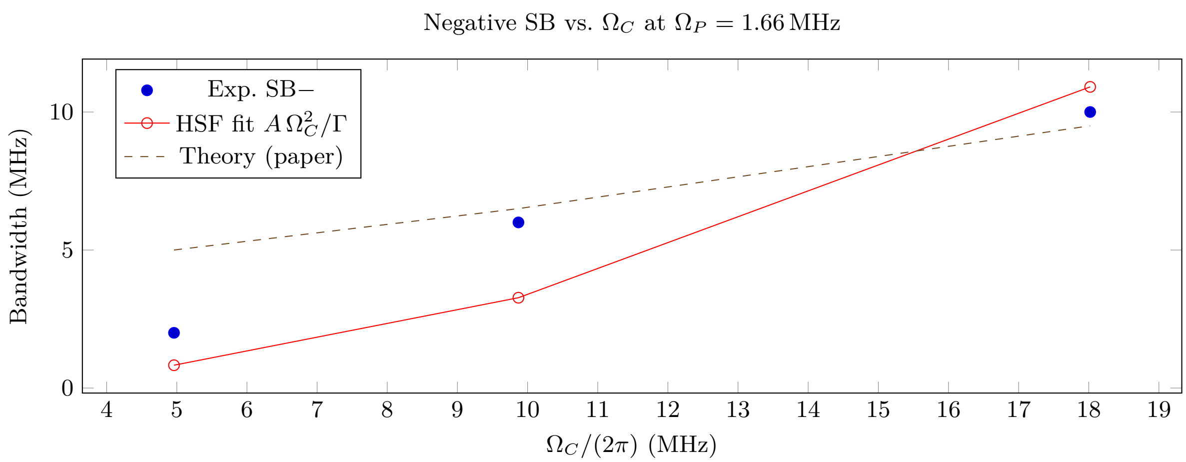

FIG. 1. Experimental SB− bandwidth vs. Ω_C with HSF fit.

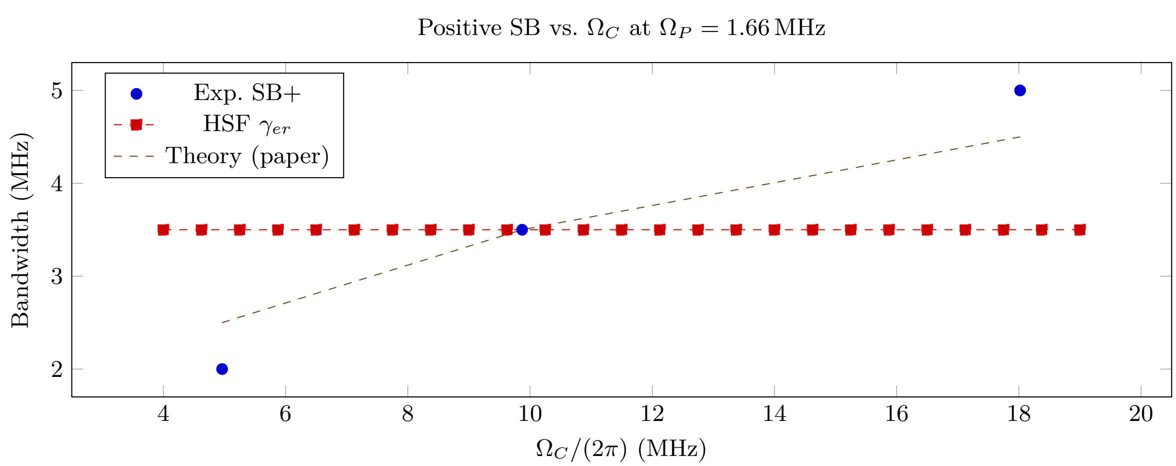

FIG. 2. Experimental SB+ bandwidth vs. Ω_C with constant-γ_{er} guide.

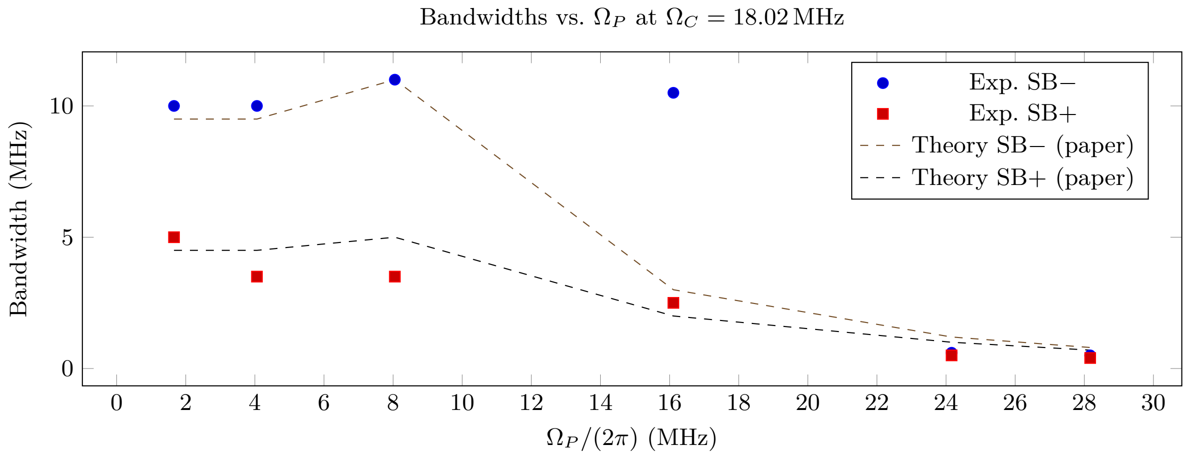

FIG. 3. Probe-driven loss of coherence at fixed Ω_C: SB+ collapses earlier than SB−, consistent with operational HSF.

VI. DISCUSSION AND SIGNIFICANCE

The one-parameter fit ($A \approx 0.204$) captures SB− across the tested Ω_C values, while SB+ remains approximately constant at $\gamma_{er} \approx 3.50\,\mathrm{MHz}$ for fixed, modest Ω_P. At larger Ω_P, both bands degrade, consistent with probe-induced back-action and inhomogeneous broadening beyond the minimal scaling. Importantly, HSF here is explicitly an interpretive layer on standard EIT/Rydberg dynamics: it emphasizes the separation of fast (optical) and slow (Rydberg) operational scales without altering the underlying equations.

VII. CONCLUSION

A minimal scaling—$\Delta f_- \propto \Omega_C^2/\Gamma$ and $\Delta f_+ \approx \gamma_{er}$—and its HSF interpretation account for the magnitude and asymmetry of sideband bandwidths in strongly-driven Rydberg atoms. The perspective clarifies optimization levers (increase Ω_C; avoid excessive Ω_P; reduce γ_{er} via environment control) and suggests further tests of universality across species and levels.

[1] M. Fleischhauer, A. Imamoglu, and J. P. Marangos, “Electromagnetically induced transparency: Optics in coherent media,” *Rev. Mod. Phys.* **77**, 633–673 (2005).

[2] A. K. Mohapatra, T. R. Jackson, and C. S. Adams, “Coherent Optical Detection of Highly Excited Rydberg States Using Electromagnetically Induced Transparency,” *Phys. Rev. Lett.* **98**, 113003 (2007).

[3] D. Shylla, N. Prajapati, A. P. Rotunno, N. Schlossberger, D. Manchaiah, W. J. Watterson, A. Artusio-Glimpse, S. Berweger, M. T. Simons, and C. L. Holloway, “Observation of Asymmetric Sideband Generation in Strongly-Driven Rydberg Atoms,” NIST Data Publication Version 1.0.0 (2024), DOI: 10.18434/mds2-3366.