

Rydberg-atom frequency upconversion as a sensitive tool for microwave/mm-wave sensing and radiometry

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ABSTRACT

Traditional microwave and millimeter-wave (mm-wave) sensing architectures are fundamentally constrained by the thermal noise of metallic components and the noise figures of semiconductor low-noise amplifiers. To achieve high sensitivity, classical radiometers typically require cryogenic cooling, which severely limits their portability and operational versatility, creating a critical bottleneck for space-borne instruments and satellite-based remote sensing. Rydberg atoms, highly excited atomic states with extreme polarizabilities, offer a disruptive alternative by acting as direct, all-optical transducers of electromagnetic fields. Building upon continuous microwave-to-optical conversion [Borówka et al., *Nat. Photonics* 18, 32 (2024)] and optically-biased nonlinear interferometry [Borówka et al., *Nat. Commun.* 16, 8975 (2025)], we present a room-temperature Rydberg sensing platform operating in a regime of near-zero intrinsic noise. By mapping microwave and mm-wave thermal signals directly onto an optical carrier followed by single-photon counting in the optical domain, this approach bypasses traditional electronic thermal floors, demonstrating room-temperature radiometric sensitivities below 1 Kelvin per 1-second integration time. With broad frequency coverage spanning 40 GHz to 600 GHz bands, inherent SI traceability without external calibration, and low Size, Weight, and Power (SWaP) payload requirements, Rydberg atomic radiometry provides a transformative framework for future satellite optics, environmental monitoring, planetary science, and deep-space 6G communication networks.

Keywords: Rydberg atoms, frequency upconversion, quantum radiometry, microwave sensing, millimeter-wave optics, space payloads, SI traceability

1. INTRODUCTION AND SPACE OPTICS CONTEXT

Passive radiometry across microwave, millimeter-wave (mmWave), and sub-terahertz (sub-THz) windows is a core technology for satellite remote sensing and space astrophysics.^{1–3} Satellite-borne radiometers measure thermal blackbody radiation emitted by Earth’s atmosphere, oceans, and land. Multi-channel observations near absorption lines, such as water vapor at 22.23 GHz and 183.31 GHz, oxygen complexes around 50–60 GHz and 118.75 GHz, and sub-THz ice cloud bands above 300 GHz, provide essential vertical profiles of temperature, humidity, and cloud microphysics.^{4,5} In planetary science and radio astronomy, sub-THz radiometers track planetary atmospheres and map cosmic microwave background emissions.^{6,7}

Despite engineering maturity, classical spaceborne mmWave receivers face fundamental operational constraints.³ Conventional front-ends rely on heterodyne mixers (SIS or Schottky diodes) and high-electron-mobility transistor (HEMT) low-noise amplifiers (LNAs).^{4,6} Achieving low noise figures requires power-intensive cryogenic cooling infrastructure, imposing strict limits on satellite payload mass, power budgets, and mission lifetime. Furthermore, front-end electronic components (including waveguides, horn feeds, LNAs, and filters) are narrow-band; observing multiple atmospheric transparency windows across 40–600 GHz typically demands separate, dedicated receiver chains, multiplying payload Size, Weight, Power, and Cost (SWaP-C).^{3,4}

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Quantum sensing based on alkali Rydberg atoms offers a compelling alternative for electromagnetic metrology.^{3,8–11} Highly excited Rydberg states ($n \gg 1$) feature huge dipole transition matrix elements scaling as $\sim n^2$, endowing atomic vapors with extreme sensitivity across megahertz to terahertz frequencies.^{12–14} Unlike solid-state electronic sensors, atomic vapor cells operate at room temperature and yield self-calibrated field measurements directly tied to fundamental physical constants.^{3,8} Beyond field electrometry and wireless communication links,^{15–17} Rydberg atomic media provide a versatile non-linear optical platform for multi-wave mixing processes that coherently upconvert low-frequency RF, microwave, or mmWave photons directly into optical photons.^{18–20} Coupling this upconversion process with high-efficiency optical single-photon detectors enables passive thermal radiometry in the optical domain.^{21–23} This quantum upconversion paradigm bypasses electronic amplifier noise, offering a path toward room-temperature, shot-noise-limited radiometric sensing across multiple mmWave bands using a single atomic sensor head.

In this paper, we review the conceptual foundation and operational framework of Rydberg-atom quantum multiband radiometry tailored for space optics. Drawing inspiration from recent advances in atomic receiver technologies,^{3,14,20,24} we examine the evolution of Rydberg receivers, compare sensing modalities, detail multi-wave mixing upconversion kinetics, and evaluate the roadmap for integrating Rydberg upconversion platforms into future satellite payloads.

2. TAXONOMY OF RYDBERG SENSING ARCHITECTURES FOR SPACE APPLICATIONS

To contextualize the potential of Rydberg frequency upconversion for space optics, it is instructive to review the principal operational architectures developed for Rydberg-atom field sensing.³

2.1 Autler-Townes (A-T) Splitting Electrometry

The foundational protocol for atomic electrometry, the Autler-Townes (A-T) method, operates via Electromagnetically Induced Transparency (EIT) in a ladder-type three-level atomic system.^{8,25} A weak probe laser monitors transmission through the ground-state transition ($5^2S_{1/2} \rightarrow 5^2P_{3/2}$ in ^{87}Rb), while a coupling laser drives the intermediate state to a high-lying Rydberg state ($n^2D_{5/2}$). An incident RF or mmWave field resonant with an adjacent Rydberg state ($n'^2F_{7/2}$) induces A-T splitting of the EIT peak:

$$\Omega_{\text{RF}} = \frac{\mathbf{d} \cdot \mathbf{E}_{\text{RF}}}{\hbar} = 2\pi\Delta\nu_{\text{AT}}, \quad (1)$$

where $\mathbf{d}$ is the calculated transition dipole moment and $\Delta\nu_{\text{AT}}$ is spectral splitting. Because dipole matrix elements are known with sub-percent theoretical accuracy, A-T splitting provides absolute SI-traceable field calibration without external reference standards.⁸ However, minimum detectable fields are limited by EIT linewidths (typically 1–10 MHz in warm vapor cells), restricting its primary utility to high-field metrology, radar calibration, and in-orbit primary standards.³

2.2 Off-Resonant AC-Stark Shift Sensing

When the incident field is detuned from Rydberg transitions, it induces a second-order AC-Stark shift of Rydberg levels, shifting the EIT peak position.^{8,10} The level shift scales as $\Delta E_{\text{Stark}} \propto |\Omega_{\text{RF}}|^2/\Delta_{\text{RF}}$, where Δ_{RF} is detuning. While AC-Stark detection enables continuous frequency coverage between discrete transitions, its field sensitivity is significantly lower than resonant schemes, often requiring field-enhancing structures that reduce operational bandwidth.³

2.3 Atomic Superheterodyne Receiver

To achieve high sensitivity for weak signals, the atomic superheterodyne architecture introduces a strong local oscillator (LO) field ($f_{\text{LO}} \approx f_{\text{sig}}$).⁹ Interference between LO and signal fields generates a low-frequency beat note at intermediate frequency $f_{\text{IF}} = |f_{\text{sig}} - f_{\text{LO}}|$. The LO field biases the atomic medium into its steepest linear response slope on the EIT resonance curve, mixing the RF signal down to an optical intensity modulation. Atomic superheterodyne receivers achieve sub-microvolt-per-meter field sensitivities ($\sim \text{nV} \cdot \text{cm}^{-1} \cdot \text{Hz}^{-1/2}$) and phase sensitivity.^{9,11} However, instantaneous bandwidth remains constrained by EIT spectroscopic linewidths, and readout sensitivity is bounded by laser intensity noise and photodiode thermal floors.³

2.4 Fluorescence Readout and Spatial Imaging

An alternative modality involves observing radiative optical decay (fluorescence) from Rydberg states populated by RF transitions.¹⁸ RF fields drive atoms into secondary Rydberg levels that decay via cascading optical transitions. Detecting fluorescence using optical filters and camera sensors enables spatial field imaging and angle-of-arrival determination.^{3,18} While fluorescence detection eliminates direct probe laser background, the incoherent emission process discards RF phase information.

2.5 Coherent Parametric Upconversion and Multi-Wave Mixing

Parametric upconversion via multi-wave mixing represents a fundamentally distinct paradigm for atomic field sensing.^{14,20,24} Rather than inspecting modified absorption or fluorescence, multi-wave mixing establishes a closed optical excitation-deexcitation loop in the atomic medium. An incoming RF, microwave, or mmWave photon drives a Rydberg-Rydberg transition, closing a parametric wave-mixing cycle that emits a coherent optical photon at a distinct wavelength (e.g., 776 nm in Rubidium).

Parametric upconversion offers three decisive architectural advantages for space optics:

1. **Decoupling Conversion Bandwidth from EIT Linewidth:** Internal conversion bandwidth is governed by phase-matching and Doppler dynamics rather than narrow EIT absorption linewidths, achieving continuous operational bandwidths exceeding tens to hundreds of megahertz.²⁰
2. **Single-Photon Optical Detection:** Upconverted optical photons are isolated from pump lasers using spectral filters and focused onto optical single-photon detectors (SPADs or SNSPDs), bypassing photodiode thermal noise and RF amplifier noise entirely.^{14,20}
3. **Phase Preservation and Interferometric Biasing:** Multi-wave mixing maps the RF phase and amplitude directly onto the optical field. Introducing an optical bias field into the loop enables hybrid nonlinear interferometry, suppressing phase noise and optimizing conversion gain.²⁴

3. PHYSICAL PRINCIPLES OF QUANTUM FREQUENCY UPCONVERSION AND RADIOMETRY

3.1 Multi-Wave Mixing Energy Loop and Phase Matching

In ⁸⁷Rb vapor, three optical excitation fields drive ground-state atoms into a Rydberg state: a probe laser ($\lambda_p = 780$ nm) for $5^2S_{1/2} \rightarrow 5^2P_{3/2}$, a coupling laser ($\lambda_c \approx 483$ nm) for $5^2P_{3/2} \rightarrow n^2D_{5/2}$, and a decoupling laser ($\lambda_d \approx 1278$ nm) addressing $n'^2F_{7/2} \rightarrow 5^2D_{5/2}$. An incoming mmWave field at f_{MW} couples $n^2D_{5/2} \rightarrow n'^2F_{7/2}$. Emission from $5^2D_{5/2} \rightarrow 5^2P_{3/2}$ produces an optical photon at $\lambda_s = 776$ nm, closing the loop.^{14,20}

Energy conservation fixes the optical photon frequency ($\nu_s = \nu_c + f_{\text{MW}} - \nu_d$), while phase matching ($\mathbf{k}_s = \mathbf{k}_c + \mathbf{k}_{\text{MW}} - \mathbf{k}_d$) establishes a directional spatial reception pattern for the incoming mmWave field.^{3,20}

3.2 Incoherent Thermal Upconversion and Radiometric Sensitivity

For passive thermal radiometry, the upconversion receiver senses incoherent blackbody radiation.^{21,22} In the Rayleigh-Jeans regime ($hf_{\text{MW}} \ll k_B T_A$), thermal photon occupation is $n_M = k_B T_A / (hf_{\text{MW}}) = T_A / T_Q$, where $T_Q \equiv hf_{\text{MW}} / k_B$ defines the quantum single-photon temperature scale ($T_Q \approx 5.8$ K at 120 GHz).

The upconverted optical count rate registered by the single-photon detector is:

$$\bar{n}_A = \eta \Delta f_{\text{int}} n_M = \eta \frac{k_B \Delta f_{\text{int}}}{h f_{\text{MW}}} T_A \equiv G T_A, \quad (2)$$

where η is conversion efficiency, Δf_{int} is atomic conversion bandwidth, and G is radiometric gain. In the shot-noise-limited regime, counting statistics over integration time $\Delta\tau$ follow Poisson noise ($\sigma_n = \sqrt{\bar{n}_A \Delta\tau}$), yielding the Noise-Equivalent Delta Temperature (NEDT):

$$\text{NEDT} = \frac{\sigma_n}{G \Delta\tau} = \sqrt{\frac{T_A T_Q}{\eta \Delta f_{\text{int}} \Delta\tau}}. \quad (3)$$

Unlike classical Dicke radiometers where radiometric sensitivity is bounded by additive electronic amplifier noise ($\text{NEDT}_{\text{classical}} = (T_A + T_{\text{Rx}})/\sqrt{B\tau}$ with $T_{\text{Rx}} \sim 500 - 3000 \text{ K}$),^{3,4} quantum upconversion eliminates additive amplifier noise ($T_{\text{Rx}} \rightarrow 0$). Upconverting weak mmWave signals to optical photon counting enables room-temperature radiometric sensitivities about 1 Kelvin per second without cryogenic cooling.^{3,20} Improving this figure of merit will be the topic of future work on how to improve the transduction efficiency and coupling of mmWaves/microwaves in the atomic system.

3.3 Single-Photon Metrology and Thermal Field Statistics

Single-photon upconversion receivers preserve optical coherence properties and field statistics.¹⁴ Thermal radiation exhibits super-Poissonian photon bunching ($g^{(2)}(0) \approx 2$).²¹ When upconverted via multi-wave mixing, the converted optical field retains thermal photon statistics over short coherence times, while long-term integration averages fluctuations into Poissonian counting statistics. Calibrating single-photon count rates against A-T splitting measurements connects weak photon-counting readouts directly to primary SI field standards.^{3,14}

4. SPACE PAYLOAD INTEGRATION AND SWAP ADVANTAGES

4.1 Comparative SWaP and Architectural Advantages

Compared to classical electronic receivers, room-temperature Rydberg upconversion radiometers offer three principal architectural benefits for satellite payloads:

1. **Cryogenic-Free Room-Temperature Operation:** Eliminating mechanical cryocoolers dramatically reduces satellite payload mass, power consumption, and launch costs while enhancing mission reliability and lifespan.^{2,3}
2. **Hardware-Unifying Multiband Agility:** In classical receivers, observing 50 GHz, 183 GHz, and 325 GHz bands requires separate RF front-ends. In a Rydberg receiver, a single atomic vapor cell covers 40–600 GHz simply by tuning optical laser wavelengths (λ_c, λ_d) to select appropriate Rydberg levels (n, n').^{3,14,20}
3. **Photonic Integration and SWaP-C Reduction:** Micro-fabricated atomic vapor cells, diode lasers, fiber routing, and Photonic Integrated Circuits (PICs) enable compact sensor heads suitable for CubeSats and smallsat constellations.^{2,3}

4.2 Vapor Cell Control and Technical Roadmap

A key engineering requirement for space-qualified receivers is maintaining stable vapor density without optical window contamination. Vapor cells are typically controlled using a dual-zone thermal design:^{26,27} the main cell body is maintained at an elevated temperature ($70^\circ\text{C} - 85^\circ\text{C}$), while a reservoir stem is kept at a slightly lower temperature ($50^\circ\text{C} - 60^\circ\text{C}$), preventing alkali condensation on windows over multi-year space missions. Stabilization of laser systems is a common challenge among atomic experiments and typically requires a feedback loop and a very stable environment. It is also still a very challenging task in the space environment.

Transitioning to spaceflight deployment requires miniaturized optical frequency stabilization, multi-photon excitation geometries to mitigate thermal Doppler broadening, and environmental qualification under launch vibration and thermal vacuum conditions.³ Future devices will need to be fiber integrated and will rely on micro-optics and photonic elements.

5. CONCLUSION

Rydberg-atom frequency upconversion represents a paradigm shift for spaceborne electromagnetic sensing and satellite radiometry. By parametrically converting low-frequency RF, microwave, and sub-terahertz thermal signals into the optical domain via multi-wave mixing, this quantum platform bypasses classical electronic noise floors and eliminates cryogenic refrigeration. Building upon foundational advances in continuous upconversion,²⁰ optically-biased interferometry,²⁴ and THz metrology,^{3,14} Rydberg upconversion platforms provide room-temperature radiometric sensitivity, unified multiband agility across 40–600 GHz, SI traceability, and low-SWaP payload profiles for future space optics missions.

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