

Nonlinearities in atomic radio receivers: Harmonic and intermodulation distortion

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Rydberg sensors offer a unique approach to radio-frequency (rf) detection, leveraging the high sensitivity and quantum properties of highly excited atomic states to achieve performance levels beyond classical technologies. Nonlinear responses and distortion behavior in Rydberg atom receivers are critical to evaluating and establishing performance metrics and capabilities such as spur-free dynamic range and tolerance to unwanted interfering signals. We report here on the measurement and characterization of nonlinear behavior and spurious response of a Rydberg atomic heterodyne receiver. Single-tone and two-tone testing procedures are developed and implemented for measurement of harmonic and intermodulation distortion in Rydberg atomic receivers based on multiphoton Rydberg spectroscopy and radio-frequency heterodyne signal detection and demodulation in an atomic vapor. For a predetermined set of atomic receiver parameters and rf carrier wave in the super high frequency band near-resonant to a cesium Rydberg transition, we measure and characterize atomic receiver selectivity, bandwidth, roll-off, compression point (P1dB), second-order (IP2) and third-order (IP3) intercepts, and spur-free dynamic range. Receiver intermodulation distortion is characterized for the case of an interfering signal wave applied at two frequency offsets relative to the near-resonant reference local oscillator, $\Delta F/F = 10^{-4}$ at 6 dB and 10^{-6} at 22 dB single-tone bandwidths, respectively. We observe that under suitable operating conditions the atomic receiver can exhibit a suppression of harmonic and intermodulation distortion relative to that of classical receiver mixer amplifiers.

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I. INTRODUCTION

Rydberg atom-based radio-frequency (rf) sensors are a rapidly advancing quantum technology, offering transformative capabilities across rf applications [1–7]. Utilizing field-sensitive Rydberg states of atoms, these sensors provide ultrawide frequency coverage spanning dc to terahertz [8–10] in subwavelength sensing volumes [11,12] and support applications ranging from high-intensity field measurements [13,14] and detection of incoherent rf electromagnetic radiation [15], to precision metrology of over-the-air (OTA) rf electric fields at the 0.1% level [9] and *in situ* plasma-field characterization [16].

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A notable advancement has been the development of phase-sensitive Rydberg atom sensors, which incorporate a fiducial reference wave into the atomic medium, enabling direct atomic rf signal phase detection, mixing, frequency conversion, and demodulation [3]. Implementations include all-optical rf phase-sensitive detection, in which a reference local oscillator (LO) field is delivered to the Rydberg atom via an rf-modulated optical field, achieving ultrahigh rf phase resolution at optical diffraction limits [17], and rf-heterodyne reception, in which a free-space reference local oscillator field is applied to the atoms [18–20]. Additional demonstrations include continuous rf tuning using off- and on-resonant couplings [21,22] and wide multiband demodulation [23], supporting broadband, frequency-agile operation for resilient communications and wireless networks.

Leveraging early advances, atomic rf demodulation has led to the development of phase-sensitive atomic receivers for analog and digital radio communications [3,23–29]. The first Rydberg sensor device, the Rydberg field probe and measurement system [5], provided atomic rf field measurement and reception capability, with subsequent demonstrations of high-resolution near-field antenna characterizations [30]. More recently, the authors developed a compact, sub-100-liter atomic receiver (highlighted in Ref. [31]), marking a major step toward deployable Rydberg hardware, and heralding the first long-range quantum radio communication using a Rydberg atomic receiver [32].

Notwithstanding the rapid progress, critical aspects of Rydberg receivers remain unexplored: the nonlinear behavior of Rydberg atom receivers and their harmonic and intermodulation distortion (IMD) performance in rf signal reception. Nonlinear responses and distortion behavior are essential factors in evaluating the capabilities of radio-frequency receivers, particularly for determining key metrics such as spur-free dynamic range (SFDR) and resilience to unwanted interfering signals. To date, while multiple rf tones in Rydberg receivers have been explored [10,19,23], systematic methods for quantifying these nonlinear atomic systems, their performance limits, and comprehensive models of the underlying multitone atomic physics have not yet been developed.

In this work, we perform measurements and characterization of nonlinear response and spurious-signal generation in Rydberg atom rf receivers, clarifying the underlying atomic mechanisms and their impact on device-level performance. Two-tone and spurious-response tests are standard tools in classical rf engineering for evaluating spur-free dynamic range, sensitivity degradation, and receiver robustness in congested environments [33], which are translated and adapted here for quantum Rydberg sensors. We examine nonlinear effects in the quantum-optical Rydberg atom response at the receiver front end and show how these atomic processes set dynamic-range limits and distortion behavior. Because Rydberg receivers operate on fundamentally different physical principles than traditional rf systems, our measurements provide, for the first time, a physics-based framework for comparing the nonlinear performance of atomic quantum receivers with that of classical rf technologies.

This paper is organized as follows: In Sec. II, we describe the rf test setup and Rydberg atomic heterodyne receiver used to conduct the atomic rf measurements and characterization at 10 GHz. In Sec. III, we present single-tone testing of the atomic receiver and measurements of receiver selectivity including intermediate-frequency (IF) bandwidth and signal rejection ratio (SRR). Section IV presents single-tone measurement and characterization of harmonic distortion. In Sec. V, we present two-tone tests and measurements of intermodulation distortion in the atomic receiver response for in-band and out-of-band interference signals. A figure of merit (FoM) for IMD performance comparison between quantum and classical receivers is established to quantify the receiver’s nonlinear response to incident electric fields of the rf signal waves in the saturation regime, and used to benchmark performance against a classical low-noise amplifier (LNA). Section VI presents a nonlinear response model based on the Lindblad master equation. Section VII discusses the implications of the measured nonlinear behavior, followed by a concluding summary and outlook.

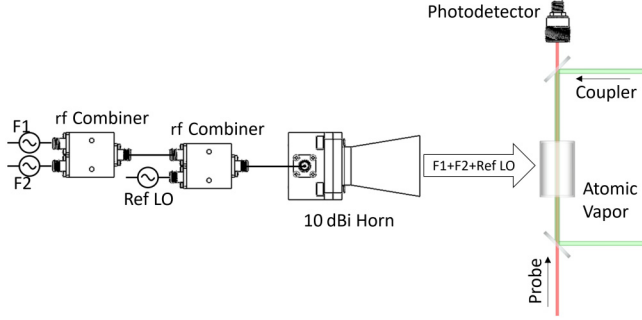


FIG. 1. Testing setup for a Rydberg atomic receiver. The F_1 and/or F_2 tones are combined with the Ref LO and injected into a 10 dBi antenna that transmits the combined rf signals OTA to an atomic vapor. The response of the rf-sensitive Rydberg atoms in the Cs vapor is measured all optically using a photodetector. The amplified photodetector output is processed using a spectrum analyzer (SA). For single-tone testing, we only apply F_1 , while for two-tone testing we apply both F_1 and F_2 .

II. RF TESTING SETUP AND RYDBERG ATOMIC HETERODYNE RECEIVER

The Rydberg receiver investigated in this work receives incident rf fields via rf-to-optical transduction by Rydberg electromagnetically induced transparency (EIT) in highly excited Rydberg states of an atomic vapor. A coherent rf reference, or LO field, is applied that couples atomic Rydberg states and provides a phase-stable reference against which weak incident OTA rf electric fields interfere in the atomic medium. The combined atom-field interaction modulates the atomic susceptibility and produces measurable changes in the optical probe transmission at an intermediate frequency that directly encodes the parameters of the rf signal, including amplitude, frequency, and phase.

The test and measurement setup for single-tone and two-tone testing of a Rydberg atomic rf-heterodyne receiver is illustrated in Fig. 1. Two signal tones at frequencies F_1 and F_2 are generated and combined with the atomic receiver reference LO at frequency F_{LO} used in phase-sensitive atomic rf-heterodyne reception [19]. The three frequencies are generated by three different signal generators synchronized to a rubidium clock, allowing independent frequency and power control of each signal tone and the LO. The combined $F_1 + F_2 + F_{LO}$ waveform is coupled into a WR-75 horn antenna with gain $G = 10$ dBi, which transmits the waveform OTA to the atomic vapor of the atomic receiver located approximately 18 cm away in the antenna far field. The atomic vapor is a cesium gas held at room temperature in a glass cell. Multiphoton Rydberg spectroscopy and EIT are used to access rf-field-sensitive Rydberg states of the cesium gas with two counterpropagating laser beams at 852 nm (probe beam) with a power of $P_p = 310 \mu\text{W}$, $w_0 = 5$ mm, and a Rabi frequency of $\Omega_p/2\pi = 2.0$ MHz and 510 nm (coupler beam) with a power of $P_c = 95$ mW, $w_0 = 4.4$ mm, and $\Omega_c/2\pi = 0.4$ MHz.

During rf signal reception, both probe and coupler lasers in the atomic receiver are frequency stabilized to linewidths below 1 kHz at target operating points near the Rydberg resonance [24] using a combination of atomic and ultrastable optical references [20]. The probe laser frequency is stabilized in the vicinity of a cesium D2 hyperfine transition [34], and the coupler laser frequency is set to couple the $6P_{3/2} \rightarrow 42D_{5/2}$ transition to access the $42D_{5/2} \rightarrow 43P_{3/2}$ Rydberg rf resonance at 9.9376 GHz. The probe beam transmission through the atomic vapor is measured on an amplified photodetector for absorption measurements of rf-induced changes to the Rydberg atom vapor. The electronic readout is measured using an SA for measurement of the atomic receiver response to applied rf signal tones. The photodetector and corresponding amplifier electronics used in all measurements had a bandwidth of 14 MHz. We perform atomic receiver testing in the super high frequency (SHF) band, and configure the atomic heterodyne receiver LO field frequency to

$F_{\text{LO}} = 9.9376$ GHz, resonant with the $42D_{5/2} \rightarrow 43P_{3/2}$ Rydberg transition. The Rabi frequency of the LO was set to an operating point of $\Omega_{\text{LO}}/2\pi = 2.8$ MHz. In a separate study, the signal-to-noise ratio (SNR) of the rf-heterodyne receiver was found to be optimal at this value [35]. In the presented measurements, either F_1 or both F_1 and F_2 signal tones are applied to the atomic receiver for single-tone and two-tone measurements, respectively. The atomic heterodyne receiver response to the applied tones is measured on the SA at intermediate frequencies $f_1 = F_{\text{LO}} - F_1$ and $f_2 = F_{\text{LO}} - F_2$, as well as at overtones and mixing products of f_1 and f_2 . All rf fields applied to the atomic receiver in the vapor cell are calibrated to absolute electric-field levels by performing atom-based rf electric-field measurements using rf-induced Autler-Townes splittings or AC-Stark shifts of Rydberg levels of the receiver atoms. The calibration measurements are performed at test fields that are sufficiently high to generate high-fidelity Autler-Townes splittings.

III. SINGLE-TONE TESTING: SELECTIVITY, IF BANDWIDTH, AND FILTER ROLL-OFF

We first perform a single-tone measurement to characterize the atomic receiver selectivity, IF bandwidth, and filter roll-off for an SHF-band signal tone following the procedure described in our earlier work [20]. The response of the atomic receiver to a tone at frequency F and field amplitude $E_F = 0.017$ V/m (-35.4 dBV/m) is measured as a function of its frequency detuning in the IF $f = F - F_{\text{LO}}$ relative to the receiver LO frequency $F_{\text{LO}} = 9.9376$ GHz resonant with the Rydberg transition with amplitude $E_{\text{LO}} = 0.21$ V/m (-13.6 dBV/m). Throughout this paper, we use dBV/m as well as V/m as the electric-field units. The log scale unit dBV/m is better to visualize the scaling in the plots.

The atomic receiver differs from conventional receivers in that the incident signal is an OTA rf electric field that is impingement onto the atoms. The atomic receiver may or may not have an antennalike structure attached to it; in any case, the atoms sense an rf electric field, as opposed to an rf voltage. The rf electric field is transmuted by the atoms into an optical signal, which is processed downstream via photodetectors and amplifiers. In contrast, a traditional system has an antenna that converts the incident OTA rf electric field into an rf voltage, which constitutes the input of the receiver. The receiver is considered separate from the antenna. An important distinction between an atomic and a conventional receiver therefore is that the atomic receiver's input is an electric field, while the conventional receiver's input is a voltage, or a power delivered into the receiver's input impedance. To compare the sensitivities of the two types of receivers, one requires the antenna factor (AF) that relates the voltage at the antenna base to the incident OTA rf electric field. The AF's dependence on wavelength and antenna gain is well known. While in the present work we are not concerned with sensitivity comparisons, it is important to understand the differences between atomic and conventional receivers to understand the units utilized in the following.

Henceforth, we adopt the notion that the atomic receiver's input is the incident OTA rf electric field present at the location of the atoms. Throughout the paper, the rf electric-field strength, E , is measured in units of dBV/m. To convert into SI units, use $E_{\text{SI}} = 1 \text{ V/m} \times 10^{E/20}$, where E is the field in dBV/m. These definitions are used for the LO and for the signal tones F , F_1 , and F_2 . The receiver's output power, P_{out} , is given by the spectrum-analyzer reading from the amplified photodetector signal at the IF frequency or frequencies. The output power P_{out} is measured in units of dBm and depends on the transimpedance amplifier gain and other operational parameters. P_{out} is subject to a noise floor. The SNR at the IF is given by the difference between P_{out} at the IF frequency in dBm and the noise floor in dBm. The dBm-level difference between the IF signal and features at other frequencies is measured in units of dBc (suppression in dB relative to the carrier). In our figures, we show incident rf fields in units of dBV/m, while P_{out} , SNR, and SRR are given in units of dBm, dB, and dBc. In this manner, the scaling laws for nonlinear effects as a function of incident rf field can be visualized well. In the text, we sometimes also provide rf field strengths in units of V/m to convey the physical electric fields the atoms are exposed to.

Figure 2(a) shows the IF signal response of the receiver to the applied tone F as a function of f for F scanned over approximately ± 1 MHz centered near F_{LO} . To quantify the selectivity, the measured

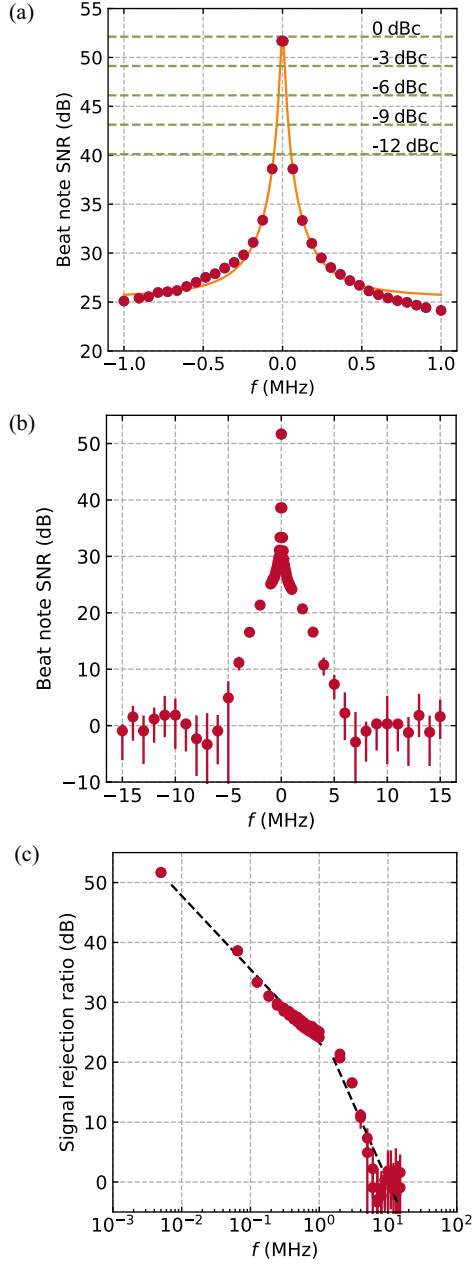


FIG. 2. Atomic receiver response as function of signal frequency detuning $f = F - F_{LO}$ relative to $F_{LO} = 9.9376$ GHz resonant with the Cs $42D_{5/2} \rightarrow 43P_{3/2}$ Rydberg transition: (a) Atomic receiver IF response SNR in dB vs f over a range ± 1 MHz. Empirical fit of the response curve to a Voigt (solid line) gives Gaussian and Lorentzian widths of $\Gamma_G/2\pi = 22.8 \pm 0.9$ kHz (FWHM = 56.6 kHz) and $\Gamma_L/(2\pi) = 12.6 \pm 1.6$ kHz, respectively. The IF bandwidths at 3, 6, 9, and 12 dB, listed in Table I, are given by the separations between the intersects between the Voigt fit and respective horizontal dashed lines. Error bars are the standard deviation from an average of three independent measurements of the beat note signal at each f . (b) Receiver IF response SNR in dB vs f over a range ± 15 MHz. (c) Atomic receiver filter roll-off plot of the signal rejection ratio in dBc vs f . Linear fits in two distinct roll-off regimes (dashed lines) yield 10 dB/decade for $f < 1.1$ MHz and 30 dB/decade for $f > 1.1$ MHz.

TABLE I. IF bandwidth of the atomic receiver at a carrier frequency of 10 GHz.

Carrier frequency (GHz)	3 dB (kHz)	6 dB (kHz)	9 dB (kHz)	12 dB (kHz)
10	61	98	145	212

response curve is fit empirically to a Voigt function, from which we obtain the peak signal response at $f = 0$ and IF bandwidths at 3, 6, 9, and 12 dB (where the response drops by 3, 6, 9, and 12 dB in power). Measured IF bandwidths are given in Table I.

In Fig. 2(c), we show the measured SRR in dBc relative to the peak signal response for $f = 10$ kHz out to $f = \pm 15$ MHz. The dashed black lines are separate linear fits to the data in two regions, in which the SRR exhibits qualitatively different roll-off behavior. In the domain $f = 10$ kHz to 1 MHz, the signal roll-off approximately follows 10 dB/decade, while from 1 to 15 MHz it approximately follows 30 dB/decade.

IV. SINGLE-TONE TESTING: HARMONIC DISTORTION

To investigate the nonlinear behavior of the receiver to an incident rf wave, we perform a single-tone measurement of nonlinear distortions within the passband of the receiver characterized in Fig. 2. This is performed using the testing setup shown in Fig. 1, with an applied tone $F_1 = 9.9377$ GHz that is offset from the $F_{LO} = 9.9376$ GHz by $f_1 = +100$ kHz approximately at the 6 dB IF bandwidth. No second tone F_2 is applied for this measurement. The measurement is performed at a fixed receiver LO field strength $E_{LO} = 0.21$ V/m (-13.6 dBV/m), and by varying the electric-field strength E_1 of F_1 and recording the f_1 signal response on the SA. The top plot in Fig. 3 shows power spectra of the response measured on the SA over a span of 50–350 kHz for two F_1 field strengths. P_{out} is the power measured at the photodetector in the IF domain. At a field strength $E_1 = 0.02$ V/m (-34.0 dBV/m), approximately one order of magnitude lower than the receiver's LO field strength, the fundamental f_1 beat note is measured at a signal level of 25 dB. Increasing the field strength by 20 dB to $E_1 = 0.2$ V/m (-14.0 dBV/m), a level comparable to the receiver's E_{LO} field level, second and third harmonics emerge at frequencies (and signal levels) $f_2 = 200$ kHz (29.5 dB) and $f_3 = 300$ kHz (12.8 dB), respectively, as a result of harmonic mixing of the tone and local oscillator fields by the nonlinear atomic medium. The bottom plot of Fig. 3 shows the received signal power at f_1 and the harmonic overtones f_2 and f_3 generated by the atomic receiver as a function of electric field E_1 of the applied tone F_1 in units of dBV/m. The field is calibrated using the receiver Rydberg atoms. A linear fit to the measured f_1 response over the applied field range $E_1 < -20$ dBV/m gives a slope of $P_{out}(\text{dBm})/E_1(\text{dBV/m}) = 0.924 \pm 0.016$, as expected for the first-order fundamental response, and allowing the designation of the P1dB compression point at an F_1 field strength equal to $E_1 = -13.6$ dBV/m. Similarly, we measure linear slopes for the f_2 second harmonic and f_3 third harmonic overtones to be 1.75 ± 0.05 and 2.8 ± 0.15 , respectively, in good agreement with expected values of 2 and 3. The second-order intercept (IP2) and third-order intercept (IP3) of the harmonic distortion products are also obtained, and nearly coincide at the F_1 field strength of $E_1 = 12.5$ dBV/m.

While the results in Fig. 3 mimic those of conventional receivers, it must be stressed that linearity and nonlinear distortion of the atomic receiver are not due to the characteristics of electronic components but are due to the high-order electric-field mixing behavior of the atomic medium. The resemblance of the scaling found for the atomic receiver with the scaling expected for conventional receivers, including the near-linear response at the fundamental IF frequency, presents a valuable finding. We note that, at P1dB in Fig. 3(c), the second harmonic is at about 17 dB below the fundamental, corresponding to -17 dBc second-harmonic distortion (SHD). Noting that SHD is our leading term of the total harmonic distortion (THD), our present result falls several dB short of the acceptable THD level for conventional receivers (which is about -20 dBc). However, given the

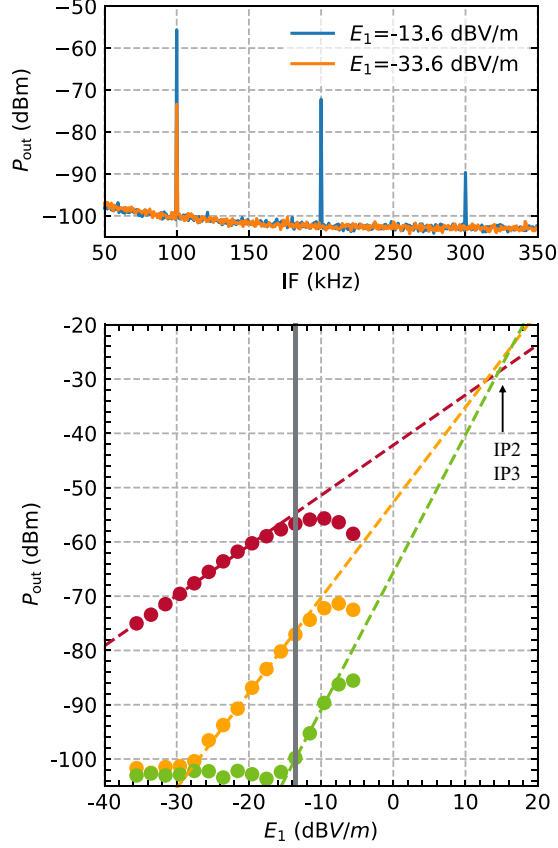


FIG. 3. Top: Power spectra of the receiver response measured on the SA for a single tone F_1 applied at the vapor cell with electric-field amplitudes $E_1 = 0.021$ V/m (-33.5 dBV/m) (orange) and 0.209 V/m (-13.5 dBV/m) (blue). Bottom: Measured receiver power for f_i fundamental and higher harmonics $i = 1, 2$, and 3 as a function of applied tone E_1 field in units of dBV/m. Linear slopes (dashed lines), the measured f_1 P1dB compression point at $E_1 = -13.6$ dBV/m (vertical solid line), and f_2 and f_3 IP2 $\approx$ IP3 ≈ 12.5 dBV/m intercept points are indicated.

novelty of the atomic receiver and noting that the instrument has not been fully optimized yet, we believe this to be a promising initial result.

V. TWO-TONE TESTING: INTERMODULATION DISTORTION

Next, we investigate the nonlinear response of the atomic receiver for intermodulation distortion in the presence of an additional interfering signal tone. We perform two-tone atomic receiver testing using the setup shown in Fig. 1. In this process, we simultaneously apply F_1 , as done previously, along with a second tone, F_2 , to the atomic receiver, which is configured to operate at a fixed $F_{\text{LO}} = 9.9376$ GHz. The response of the atomic receiver to the tones and resulting intermodulation products are observed directly at the IF on the SA, where the applied F_1 and F_2 tones each get simultaneously demodulated by the Rydberg atoms and reference F_{LO} field to their respective IF at f_1 and f_2 . We investigate two different conditions for the applied tones: (1) $\Delta F/F = 10^{-6}$, where $\Delta F = F_2 - F_1 = 10$ kHz for $F_1 = +100$ kHz, with both tones at approximately the 6 dB IF bandwidth of the receiver (see Fig. 2 and Table I), and (2) $\Delta F/F = 10^{-4}$, where $\Delta F = F_2 - F_1 = 1$ MHz for $F_1 = +100$ kHz, with the second tone at a comparably higher frequency at the 22 dB IF bandwidth, well

outside of the resonant line shape shown in Fig. 2(a). In all cases, the field amplitudes of both tones are equal.

A. Intermodulation distortion at $\Delta F/F = 10^{-6}$

To test IMD at $\Delta F/F = 10^{-6}$, we set $F_1 = 9.937\,70$ GHz, where $f_1 = F_1 - F_{\text{LO}} = 100$ kHz, and $F_2 = 9.937\,71$ GHz, where $f_2 = F_2 - F_{\text{LO}} = 110$ kHz producing two simultaneous IF responses at $f_1 = 100$ and $f_2 = 110$ kHz, with a two-tone frequency separation of $\Delta F = F_2 - F_1 = 10$ kHz and a relative frequency separation of $\Delta F/F = 10^{-6}$. Figure 4 shows the results of this two-tone measurement. In panel (a), we show an IMD map that is constructed by monitoring each of the detected IMD peaks in the IF range spanning from 10 to 300 kHz (x axis) for a selection of applied rf electric-field strengths at the atoms' location for the two tones F_1 and F_2 (y axis). Each dot on the IMD map represents a detected peak on the SA, and the size of the dot indicates the relative signal strength for that peak. The color code of the peaks in the IMD map is chosen such that the fundamental peaks (F_1 and F_2) are black, second-order IMD peaks are red, third-order ones are yellow, fourth-order ones are light green, fifth-order ones are dark green, sixth-order ones are cyan, seventh-order ones are teal, eighth-order ones are purple, and peaks that represent IMD of orders higher than 8 are gray. This color notation will be used throughout this paper. Here, we observe that intermodulation starts to develop as the electric-field strength increases. The plot in panel (b) is a cut out of two traces from the map in panel (a), showing the spectral response of the atomic signal for two different electric-field strengths of F_1 and F_2 . The intermodulation peaks are indexed as $(n_1 \text{ and } n_2)$ such the IMD peak order can be identified by the peak frequency in the IF spectra by $f_{n_1, n_2} = n_1 \times f_1 + n_2 \times f_2$, where the order of the IMD is given by $N = |n_1| + |n_2|$. For example, the first peak labeled $(-1, 1)$ represents a second-order IMD ($N = 2$) and shows up at $f_{-1, 1} = 10$ kHz, and the second peak labeled $(-2, 2)$ represents a fourth-order IMD ($N = 4$) and shows up at $f_{-2, 2} = 20$ kHz. The index scheme will also be used throughout this paper and the IMD peaks will be colored using the previously described color scheme. In this plot, we can clearly identify the IMD peaks up to the eighth order ($f_{4, -4}$).

The bottom plot in panel (c) shows the detected signal strength of the fundamental peaks and the two strongest third-order IMD ($f_{2, -1} = 90$ kHz and $f_{-1, 2} = 120$ kHz) as a function of electric-field strength. The vertical line in the plot serves as a reference marking the LO field signal strength. The dashed lines represent a linear fit of the data within the range before saturation ($E_1 = E_2 < -20$ dBV/m). For the fundamental response at f_1 and f_2 , we observe a near-linear behavior with slopes of 0.97 ± 0.03 and 0.92 ± 0.03 , respectively, and a 1 dB compression point at -20 (-22) dBm for f_1 (f_2). The corresponding rf electric fields of the two tones at the 1 dB compression points are approximately -17 dBV/m. The 1-dB compression points are determined by solving for where the data point deviates the linear fit by 1 dB. The observed slopes are close to a slope of 1, as expected for fundamental tones in classical receivers. Regarding the selected intermodulation peaks in the plot ($f_{2, -1} = 90$ kHz and $f_{-1, 2} = 120$ kHz), the linear fit indicates a slope of 2.1 ± 0.08 , which is suppressed relative to the expected slope of 3 for classical rf systems. We attribute these differences in the atomic heterodyne receiver to the nonlinear responses and multiwave mixing effects present in the quantum Rydberg EIT system, which are anticipated to exhibit deviations from classical rf electronics. From the fit, we measured an $\text{IP3} = 2.7$ dBV/m. It is imperative to emphasize that these additional peaks are not attributable to any electronics artifact in the detection or on the backend of the receiver. Rather, they solely arise as the high-order effects of the atoms themselves. In rf-heterodyne measurements, the atoms experience the rf electric fields from the LO and the signal (F_1 and F_2) fields. According to the superposition principle of electromagnetism in free space, the electric-field amplitudes due to multiple field components are a linear sum over all components. As is commonly the case, harmonic generation and IMD arise as a result of nonlinear response of an element (which may be a diode, an amplifier, or a receiver system) at high electric fields. In the present case, it is the nonlinear response of the atomic EIT medium to the electric field that gives rise to harmonic generation and IMD.

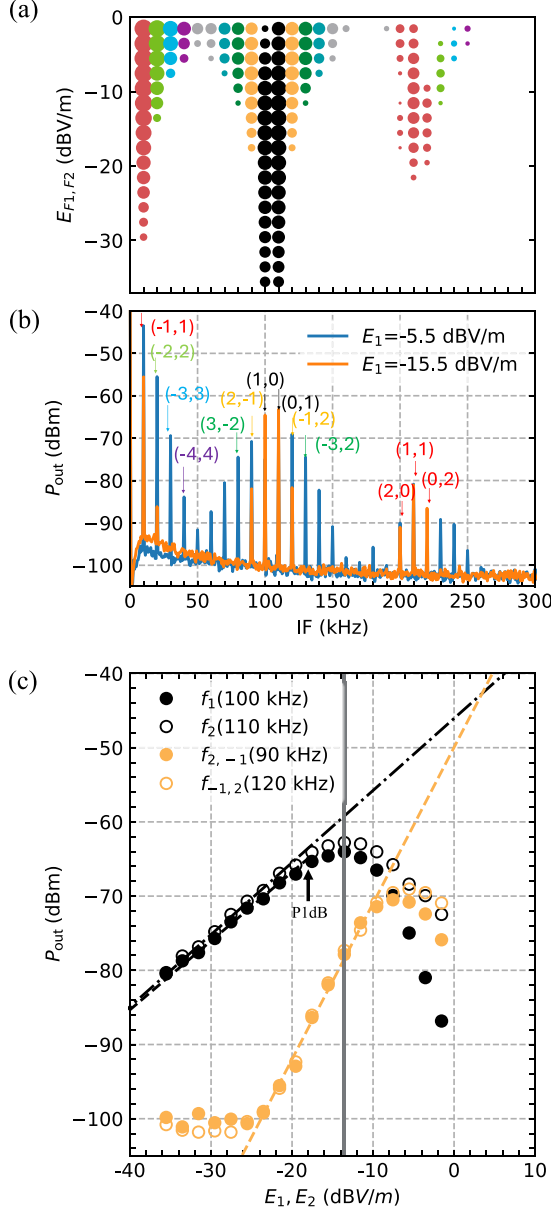


FIG. 4. Atomic receiver two-tone testing at $\Delta F/F = 10^{-6}$: (a) IMD map showing the intermodulation peaks in the IF range spanning from 10 to 300 kHz (x axis) for a selection of applied rf electric field for the two tones F_1 and F_2 (y axis). The dot size and color scheme are explained in the text. (b) Power spectra of the receiver response in the IF measured on the SA for two tone strengths $F_1 = 9.93770$ GHz and $F_2 = 9.93771$ GHz applied at the vapor cell with electric-field amplitudes $E_1 = E_2 = -5.5$ dBV/m (orange) and $E_1 = E_2 = -15.5$ dBV/m (blue). These spectra were taken at 1 kHz resolution bandwidth (RBW) to accelerate the acquisition with such a large frequency span of 3 MHz, resulting in an elevated noise level. The peak indexing scheme is explained in the text. (c) Receiver IF output power in dBm vs two-tone applied electric field $E_1 = E_2$ in dBV/m for the fundamental products (1, 0) and (0, 1) and third-order IMD (2, -1) at $f_{2,-1} = 90$ kHz and (-1, 2) at $f_{(-1,2)} = 120$ kHz. Linear fits are indicated in dashed lines, yielding the measured P1dB = -17.5(-15.5) dBV/m for f_1 (f_2) (black arrow), IP3 = 2.7 dBV/m for $f_{-1,2}$ to f_1 , and FoM = IP3 - P1dB = 20.2 dB.

B. Intermodulation distortion at $\Delta F/F = 10^{-4}$

We also tested IMD at $\Delta F/F = 10^{-4}$ by keeping $F_{\text{LO}} = 9.937\,60$ GHz and $F_1 = 9.937\,70$ GHz, but setting the frequency of the second tone near the end of the receiver's linear response (refer to Fig. 2), $F_2 = 9.938\,71$ GHz. This increases f_2 to 1.110 MHz and leads to an absolute frequency separation of $\Delta F = F_2 - F_1 = 1.01$ MHz. Figure 5 shows the results for the two-tone measurement with $\Delta F/F = 10^{-4}$. Figure 5(a) shows an IMD map that illustrates all the IMD peaks in the IF band as a function of the F_1 and F_2 electric-field strengths at the atoms' location (as defined previously). In this plot, we show that the atomic vapor continues to mix down the applied tones to two intermediate frequencies f_1 and f_2 . In comparison with the results in Fig. 4(a), we observe fewer peaks. This difference is a result of the large ΔF , which allows only a few IMD frequencies ($f_{n1,n2}$) within the atomic IF response bandwidth. For instance, for the $\Delta F/F = 10^{-6}$ case in Sec. V A, the sixth-order IMD peak $f_{-3,3}$ occurs at 30 kHz, which is well within the atomic IF bandwidth, whereas in the present $\Delta F/F = 10^{-4}$ case the same IMD peak is at 3.030 MHz, which is outside of the atomic IF bandwidth (Table I).

In the measurement presented in Fig. 5, the two tones were set to have the same electric-field strength, but the fundamental tones f_1 and f_2 differ in signal strength, with the signal at f_2 being 10 dB lower than f_1 . This finding is in good qualitative agreement with Fig. 2(c), which shows approximately 10 dB drop in IF response between 100 kHz and 1 MHz. Figure 5(b) shows a selection of two SA traces, displaying the spectral response of the atomic signal for two different electric-field strengths of the signals at F_1 and F_2 , with the IMD peaks labeled as defined previously. In this plot, we observe IMD products up to the fifth order ($f_{-3,2} = 1920$ kHz).

Figure 5(c) shows the detected signal strength of the fundamental peaks and the two strongest third-order IMDs ($f_{-2,1} = 910$ kHz and $f_{-1,2} = 2120$ kHz) as a function of electric-field strength. The vertical line in the plot marks the field of the LO. The dashed lines show linear fits of the data in the subsaturation regime $E_1 = E_2 < -20$ dBV/m; the fits are extrapolated to the right margin of the plot. In the regime $E_1 = E_2 \gtrsim -20$ dBV/m, we observe a near-linear behavior for the fundamental response at f_1 and f_2 , with slopes of 0.87 ± 0.01 and 0.91 ± 0.02 , respectively, which is near the expected value of 1. The P1dB compression points correspond to rf electric fields of the two tones equal to -16.5 and -15.5 dBV/m for f_1 and f_2 , respectively. For both third-order IMD peaks selected in Fig. 5(c), the linear fits have slopes of 1.6 ± 0.2 , which is significantly less than our finding in the analogous measurements at $\Delta F/F = 10^{-6}$ in Fig. 4(c). We also recall, for comparison, that for third-order IMD in classical rf systems a slope of 3 would be expected. Again, we attribute this difference to the quantum nature of the Rydberg receiver.

The IP3 points for the $\Delta F/F = 10^{-4}$ measurements in Fig. 5(c) are determined to be 19.3 and 11.9 dBV/m for f_1 and f_2 , respectively. It is noteworthy that these values are fairly large: They contrast with analogous measurements at $\Delta F/F = 10^{-6}$ in Fig. 4(c), where we found an IP3 as low as 2.7 dBV/m. In view of our finding regarding the slopes of the third-order IMDs (see the previous paragraph), this difference is largely attributed to the comparatively small slope of the third-order IMD found for $\Delta F/F = 10^{-4}$. A smaller slope of the third-order IMD pushes the IP3 points farther out. Moreover, for $\Delta F/F = 10^{-4}$ [Fig. 5(c)] the IP3 for f_2 is about 7 dB lower than that for f_1 . We attribute this behavior to the fact that f_2 is near the atomic IF bandwidth, where the atomic response is reduced by about 10 dB relative to the response at f_1 , pushing the corresponding IP3 to a lower value.

In classical rf systems, IMD is quantified by the power ratio between the fundamental and the third-order IMD responses. The SFDR of a receiver is given by $\frac{2}{3}(\text{IP3}_{\text{out}} - N_0)$, where N_0 is the noise floor of the nonlinear or harmonic component [36] at 1 Hz RBW on the SA and IP3_{out} is the output power at the IP3 point. In Fig. 5(c), for f_1 and the third-order IMD we read, on the y axis, an IP3_{out} of -34 dBm. Also, the SA noise floor was $N_0 = -121$ dBm (not shown in the figure). We therefore determine an SFDR of the atomic receiver of $\frac{2}{3}(\text{IP3} - N_0) = 58$ dB.

To benchmark the IMD performance of the atomic quantum receiver to that of a typical classical receiver, we introduce an FoM for distortion, defined as the difference between the IP3 and P1dB

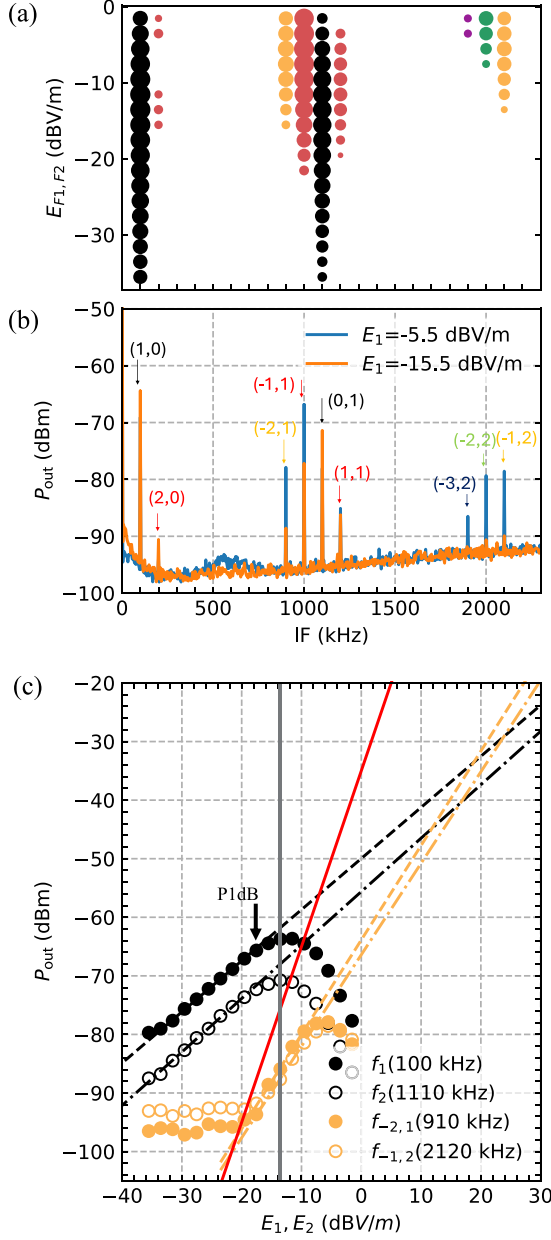


FIG. 5. Atomic receiver two-tone testing at $\Delta F/F = 10^{-4}$: (a) IMD map showing the intermodulation peaks in the IF range spanning from 10 kHz to 2.300 MHz (x axis) for a selection of applied rf electric fields for the two tones $F_1 = 9.937\,70$ GHz and $F_2 = 9.938\,71$ GHz (y axis). (b) Power spectra of the receiver response in the IF measured on the SA for $E_1 = E_2 = E_{low} = -15.5$ dBV/m (red) and $E_1 = E_2 = E_{high} = -5.5$ dBV/m (orange). The peak indexing scheme is explained in the text. (c) Receiver IF output power in dBm vs two-tone applied electric field $E_1 = E_2$ in dBV/m for the fundamental products (1, 0) (black dots) and (0, 1) (black circles) and the third-order IMD $(-2, 1)$ (yellow dots) at $f_{-2,1} = 910$ kHz and $(-1, 2)$ (yellow circles) $f_{-1,2} = 2120$ kHz. Here, the RBW is 1 Hz. Linear fits are indicated in dashed lines, yielding the measured $P_{1dB} = -16.5(-15.5)$ dBV/m for f_1 (f_2) (black arrow), $IP_3 = 19.3$ (11.9) dBV/m for $f_{-2,1}$ to f_1 (f_2), and $FoM = IP_3 - P_{1dB} \approx 35$ dB. The red line represents the saturation behavior of the classical LNA, ZX60-06183LN+, discussed in the text.

compression point as $\text{FoM} = \text{IP3} - \text{P1dB}$, where IP3 and P1dB are read on the input (x axis) in Fig. 5(c). This metric quantifies the additional signal strength that would have to be applied to the input of the receiver (whether classical or quantum) before a third-order nonlinear response would become significant relative to the receiver's compression point. From Fig. 5(c), we measure an FoM for the atomic receiver of approximately 35 dB, which compares favorably to many classical LNAs at 10 GHz. These LNAs typically exhibit a distortion FoM of 12 dB or less (see, e.g., commercial devices from Mini-Circuits part No. ZX60-06183LN+ or Pasternack part No. PE15A1032). An illustrative third-order IMD response ($f_{-2,1}$) for the classical LNA with an $\text{FoM} = 12$ dB is overlaid in Fig. 5(c) in the red line. The red line is plotted under the assumption that the third-order outputs of the atomic receiver and the classical LNA match at ≈ -20 dBV/m, where third-order IMDs begin to appear in our measurement. It has a slope of 3 and intercepts with the atomic receiver's IF curve earlier than the actual IMD products of the atomic receiver, which points at an advantage of the atomic receiver over the LNA in terms of IMD.

There are two important distinctions to keep in mind in the above comparisons. First, the atomic receiver measures OTA free-space rf signal waves, while LNAs process electronic rf signals. Second, not unrelated to the first, the FoM comparison uses a relative metric and does not provide an absolute rf signal metric measurable as an FoM for distortion by both receiver types. Obtaining an absolute signal rf field metric that can be compared for both receiver types would require specific assumptions about the antenna aperture or similar transducer used to convert a free-space rf signal field to an analogous the rf electric signal input into an LNA. Since the antenna transducer details vary substantially for different antenna types and applications of interest, it is not incorporated in the comparison presented in our paper. Generally, and without regard to the front-end antenna used, the atomic quantum receivers can exhibit a greater tolerance to nearby interference signals compared to classical LNAs within their respective dynamic ranges [37].

VI. NONLINEAR RESPONSE MODELING

The nonlinear response of the atomic receiver is modeled by time-dependent solution of the Lindblad master equation for the underlying four-level system. Indices 1, 2, 3, and 4 refer to ground state, excited state, nD -Rydberg state, and rf-coupled Rydberg state, respectively. We numerically find time-dependent solutions for the ground-excited-state coherence, $\rho_{1,2}(t)$. Spectral analysis of $\rho_{1,2}$ then yields the signals, harmonics, and mixing products:

$$\dot{\rho} = \frac{\partial \rho}{\partial t} = -\frac{i}{\hbar} [\mathbf{H}, \rho] + \mathcal{L}, \quad (1)$$

where $\mathbf{H}$ represents the Hamiltonian

$$H = \hbar \begin{pmatrix} 0 & \Omega_{1,2}/2 & 0 & 0 \\ \Omega_{1,2}^*/2 & \delta_2 & \Omega_{2,3}/2 & 0 \\ 0 & \Omega_{2,3}^*/2 & \delta_3 & \Omega_{3,4}/2 \\ 0 & 0 & \Omega_{3,4}^*/2 & \delta_4 \end{pmatrix}, \quad (2)$$

where δ_n are the dressed-state energies,

$$\begin{aligned} \delta_1 &= 0, \\ \delta_2 &= -\Delta_P + k_P v, \\ \delta_3 &= \delta_2 - \Delta_C - k_C v, \\ \delta_4 &= \delta_3 - \Delta_{\text{rf}}, \end{aligned} \quad (3)$$

where v is the atom velocity along the laser beam directions, and Δ_P and Δ_C are the probe and coupler detunings from the respective atomic transitions at zero velocity. k_* are corresponding wave

numbers, which are defined positive. Δ_{rf} is the detuning of a selected rf reference frequency, ω_{ref} , from the Rydberg microwave transition frequency. One may chose $\Delta_{\text{rf}} = 0$.

The four atomic levels are coherently coupled by the EIT probe and coupler lasers, the rf LO field, and up to two signal field (SIG). $\Omega_{n,m}$ are the complex Rabi frequencies between levels n and m . The net rf Rabi frequency depends on the angular frequency differences η_{LO} , η_1 , and η_2 relative to the selected rf reference frequency, $\eta_{\text{LO}} = \omega_{\text{LO}} - \omega_{\text{ref}}$, etc.,

$$\Omega_{3,4} = \Omega_{\text{LO}} \exp(-i\eta_{\text{LO}}t) + \Omega_1 \exp(-i\eta_1t) + \Omega_2 \exp(-i\eta_2t). \quad (4)$$

There, the fixed complex Rabi frequencies Ω_{LO} , Ω_1 , and Ω_2 for LO, SIG 1, and SIG 2 may incorporate additional fixed phases.

The Lindblad operator $\mathcal{L}$ accounts for all atomic decays and decoherence processes, which are the natural decay of the excited state, state-dependent collisional dephasings for all four levels, and a global atom recycling rate related to the inverse of the typical atom-field interaction time.

The time-dependent complex absorption coefficient for the probe then is

$$\alpha_{1,2}(t) = \frac{4\pi d^2 n_V}{\hbar \epsilon_0 \lambda_P |\Omega_{1,2}|} \int dv P(v) \rho_{12}(v, t), \quad (5)$$

with the normalized one-dimensional Maxwell distribution $P(v)$, the m -averaged dipole moment $d = 1.99ea_0$ for the Cs D2 line, the atom density n_V in units of m^{-3} , and the probe wavelength λ_P .

We then obtain the imaginary parts of the complex Fourier transform of $\alpha_{1,2}$, denoted by $\tilde{\alpha}_{1,2}(\omega_{\text{IF}})$, where the IF frequency domain of ω_{IF} covers both positives and negatives. Note that $\tilde{\alpha}_{1,2}$ is real-valued in this definition. The receiver signal power at $|\omega_{\text{IF}}|$, denoted by $P_{\text{out}}(\omega_{\text{IF}})$, then equals the sum of the squares of positive- and negative-frequency amplitudes, $\tilde{\alpha}_{1,2}(\omega_{\text{IF}})$ and $\tilde{\alpha}_{1,2}(-\omega_{\text{IF}})$, with positive ω_{IF} . Note that in this formulation the argument ω_{IF} can be any frequency in the IF band, including the nominal IF frequencies of the signals, $|\omega_{\text{LO}} - \omega_1|$ and $|\omega_{\text{LO}} - \omega_2|$, overtones of these, and IMD products.

Before proceeding, we highlight several key aspects of our model and analysis. Equations (1)–(4) show that the optical fields and rf reference ω_{ref} are treated using a common multicolor dressed-atom approach, while the additional rf tones are incorporated through an interaction-picture approach. The interaction-picture approach is necessary because the atomic bandwidth allows the Rydberg atom to respond to almost all of the applied rf frequencies simultaneously; a steady-state multi-frequency model cannot be applied to the full set of rf tones. This is evident from the phases of the complex rf frequencies in Eq. (4), which oscillate at the rf frequency differences. It also is manifest that IMD and harmonic distortion arise from the rf frequency mixing by the Rydberg atoms, which occurs when rf field strengths and intensities exceed the atomic linear-response region (the linear limit is illustrated, e.g., by the orange curve in Fig. 3, top panel). The atomic mixing processes generate higher-order components in the atomic coherence $\rho_{12}(\omega_{\text{IF}})$, which are then measured. Importantly, the photoreceiver and the remainder of the classical detection chain are linear and do not contribute to the generation of IMD and harmonic tones. Consequently, the nonlinear phenomena described here originate in the atomic dynamics, and the physics therefore applies broadly to Rydberg rf receivers, independent of the specific classical signal chain hardware.

The model yields output powers at the IF frequencies, at their overtones, and at the IMD frequencies. While additional details of the simulation work are beyond the scope of the present paper, in Fig. 6 we show simulated results on third-order IMD products for a selected case. The simulated input field is given in units of dBV/m and the output power in units of dBm. In the computation, the SIG fields are entered in the form of respective Rabi frequencies, which are proportional to the SIG electric fields. The proportionality constant, which includes the Rydberg transition's electric dipole moment, is accounted for by an additive constant on the dBV/m scale. The receiver output $P_{\text{out}}(\omega_{\text{IF}})$ is modeled as described above. The ω_{IF} values of interest include the fundamental IF frequencies, their harmonics, and various IMD frequencies. Multiplicative constants

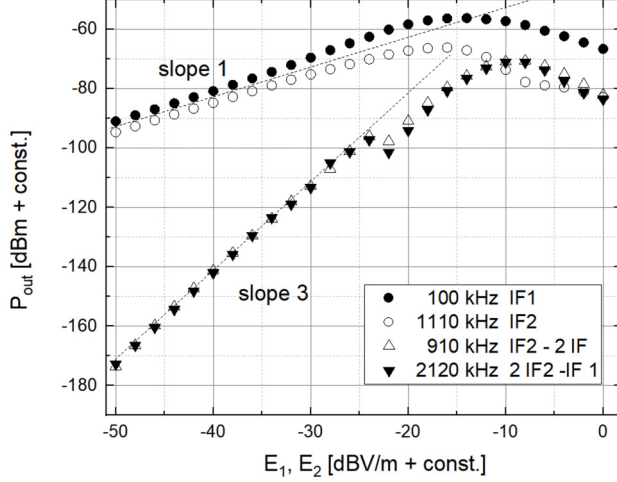


FIG. 6. Simulation result for parameters similar to those used in Fig. 5. Symbols show simulated data. Lines with the indicated fixed slopes have been added into the plot to estimate the slopes of the data. Circles show experimental data obtained for the IF signals. IF and selected IMD frequencies are indicated in the legend. It is seen that both IF signals have a slope near 1. The lower IF frequency has the stronger response, and the higher IF frequency rolls off slightly before the lower IF. These observations closely match the experimental data in Fig. 5. The triangles show the third-order IMD products indicated in the legend. The IMD products have a slope near 3 and roll off at about 5 dBV/m above the roll-off fields of the IF signals, which also is in qualitative agreement with Fig. 5. The simulation does not include noise.

that arise from vapor-cell, laser-beam, and gain parameters are accounted for by an additive constant on the dBm scale.

The model clearly shows the rise of high-order harmonics and intermodulation peaks as the rf signal power is increased. The simulation result shown in Fig. 6 is in good qualitative agreement with the corresponding measured data in Fig. 5(c). The simulation details are as follows. The probe, coupler, and LO Rabi frequencies are $\Omega_{1,2} = 2\pi \times 2.90$ MHz, $\Omega_{2,3} = 2\pi \times 0.43$ MHz, and $\Omega_{LO} = 2\pi \times 3.00$ MHz, respectively. The SIG Rabi frequencies are identical and are scanned on a logarithmic scale from $2\pi \times 0.0474$ to $2\pi \times 15$ MHz. The atom temperature is 300 K and the atom density is $2.77 \times 10^{16} \text{ m}^{-3}$. The decay rate on the probe transition is $2\pi \times 5.2$ MHz. Rydberg atoms are recycled into the ground state at rates of $2\pi \times 5$ kHz to account for the atom-field interaction time, which is limited due to transverse motion. This parameter is only marginally important, as long as it is small. Both Rydberg states have dephasing rates of $2\pi \times 20$ kHz. The probe and coupler lasers are both on-resonant for zero-velocity atoms. Notably, the slopes and roll-off characteristics in Figs. 5(c) and 6 are a good match for both the IF and the IMD products. The simulation does not include noise on the signal and inhomogeneities of both the optical and rf fields. Nonetheless, the presented simulations produce good initial results toward future modeling work and refinement.

VII. DISCUSSION

The nonlinear behaviors of atomic receivers described in this work are notably unlike those of classical LNAs and electronic systems in that they incorporate an atom-field interaction that is ultimately tied to the invariable atomic structure and fundamental physical constants. As such, unlike their classical counterparts, the nonlinear behaviors of atomic receivers are reproducible under user-determined conditions and can provide unique, controllable rf signatures on the receive side for predetermined signal sources. This can be exploited to realize transmit-receive communications modalities for secure communications, rf fingerprinting, and other applications. As a basic

example implementation, a physical encryption scheme may be employed using an atomic receiver in which the nonlinear response of a two-tone local oscillator (e.g., output shown in Fig. 4) can be switched between discrete spectra of higher-order products (e.g., by switching LO amplitudes and frequencies). The switching between spectra can serve as a coding algorithm to, for example, provide a physical frequency hop table selector in the receiver for an incident rf waveform with frequency-hopping spread spectrum modulation.

The slopes of the second and third harmonics are close to 2 and 3, the values expected for semiconductor-based systems. This similarity is noteworthy because the atomic receiver differs greatly from those, yet we find similar scalings for the second and third harmonics. We further use Fig. 3 to extract the second- and third-order intercepts, IP2 and IP3. These values commonly serve as measures to rate the nonlinearity of receivers. Higher intercepts are desired because they correspond with lower nonlinearity. The value of IP2 is relevant because the second harmonic often is the leading distortion (as is the case in our Fig. 3). The value of IP3 has an elevated importance because it also is an approximate measure for third-order IMDs (see Sec. V). The latter can be close in frequency to a (fundamental) IF and therefore hard to filter out. In Fig. 3, we find nearly coincident IP2 and IP3 values of $E_1 \approx 12.5$ dBV/m. For the atomic receiver in Fig. 3, the IP3 value is about 25 dB above P1dB, which is somewhat higher than the typical difference of 10–15 dB in conventional amplifiers. The 10 dB advantage observed in the atomic receiver likely reflects the fundamental differences in the principles of operation of atomic and conventional receivers. We also note that in conventional systems the difference IP2 - P1dB ranges between about 15 and 40 dB. In our atomic receiver, IP2 - P1dB is about 25 dB, which is in line with conventional systems.

The types of optical EIT schemes used [38–40], the intensities of the optical EIT-readout beams [41–45], and the atomic vapor-cell conditions play a role in the detailed manifestation of IMD and harmonic distortion in Rydberg receivers [46–48], without changing the atomic physics discussed in the present work. Further, similar nonlinear behavior can occur in receivers operating through nonresonant AC-Stark shifts, although the magnitude and spectral dependence of the response would differ due to the absence of a resonance.

VIII. CONCLUSION

In our study, we have presented a first comprehensive characterization of harmonic and intermodulation distortion behavior in atomic receivers. Through two-tone testing conducted in the SHF band, utilizing tones resonant to an Autler-Townes transition between Rydberg states in the atomic-receiver medium, we have observed IMD of orders higher than 6, measured the dependence of the harmonics and IMD peaks with incident rf power, obtained crucial metrics such as P1dB and IP3 points, and characterized the dynamic range and spur-free dynamic range of the system. Rydberg receivers efficiently suppress harmonic and IMD distortions outside the receiver’s instantaneous IF bandwidth, diverging from the behavior of classical receivers with wider IF bandwidths. Our observations highlight the unique and advantageous properties of atomic receivers in mitigating nonlinear effects.

While our experimental results are derived from a specific atomic receiver implementation, many of the observed phenomena, such as the presence and scaling of harmonic and intermodulation distortions, the behavior of the intermediate frequency bandwidth, and the suppression of nonlinearities, are fundamentally rooted in atomic and quantum mechanical processes. These processes are largely universal and therefore expected to generalize across similar atomic receiver systems. Although quantitative parameters like P1dB, IP3, and SFDR may vary with experimental configurations (e.g., laser parameters, cell geometry, and local oscillator power), the underlying mechanisms and trends we describe should be broadly applicable. As such, the insights offered in this work serve not only to characterize a specific device but also to inform the design and interpretation of behavior in a wider class of Rydberg rf receivers.

The narrow bandwidth of the Rydberg rf receiver evaluated in this work at 10 GHz is beneficial in suppressing IMD, harmonic mixing, and other out-of-band noise. A wider receiver bandwidth,

possible with receiver architectures implementing, for example, channel multiplexing, frequency switching, and synchronous tuning of the Rydberg atoms to maintain resonance with the LO field, may be able to combine the benefits of narrow bandwidth for suppression of nonlinear effects and noise with the benefits of the fundamental wideband tunability of Rydberg atoms for rf reception.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

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