We demonstrate an atomic radio-frequency (RF) receiver and spectrum analyzer based on thermal Rydberg atoms coupled to a planar microwave waveguide. We use an off-resonant RF heterodyne technique to achieve continuous operation for carrier frequencies ranging from DC to 20 GHz. The system achieves an intrinsic sensitivity of up to $-120(2)$ dBm/Hz, DC coupling, 4 MHz instantaneous bandwidth, and over 80 dB of linear dynamic range. By connecting through a low-noise preamplifier, we demonstrate high-performance spectrum analysis with peak sensitivity of better than $-145$ dBm/Hz. Attaching a standard rabbit-ears antenna, the spectrum analyzer detects weak ambient signals including FM radio, AM radio, Wi-Fi, and Bluetooth. We also demonstrate waveguide-readout of the thermal Rydberg ensemble by non-destructively probing waveguide-atom interactions. The system opens the door for small, room-temperature, ensemble-based Rydberg sensors that surpass the sensitivity, bandwidth, and precision limitations of standard RF sensors, receivers, and analyzers.

I. INTRODUCTION

Sensors based on quantum constituents have unique properties that distinguish them from traditional technologies. The absolute sameness of quantum particles often leads to exquisite precision, and their response and performance are accurately linked to first-principle predictions. Quantum sensors of time (atomic clocks) and magnetic fields (magnetometers) have achieved record performance, and other classes of quantum sensors are expected to follow.

Quantum sensors for radio-frequency (RF) electromagnetic fields are a swiftly emerging subset, and will be critical in the future, as ever-increasing networking and informational demands require greater capabilities to utilize the finite spectrum. But non-cryogenic quantum RF sensors do not currently match the sensitivity of traditional receivers that use standard electronics. And, until now, individual quantum RF sensor measurements have only covered small portions of the spectrum.

Here, we present a near-room-temperature RF quantum sensor based on thermal Rydberg atoms that operates continuously from 0 to 20 GHz, and rivals the performance of commercially-available spectrum analyzers with high sensitivity, 4 MHz instantaneous bandwidth, and over 80 dB of linear dynamic range. Our sensor improves upon previously demonstrated Rydberg RF sensors, by 1) improving sensitivity to RF power by confining the RF field in a small mode volume that closely matches the sensing volume and 2) utilizing an off-resonance heterodyne technique to greatly boost the sensitivity at arbitrary frequencies, far from a resonant Rydberg transition. The system can be operated with or without a low-noise preamplifier for the input RF signals, with numerous possible paths for miniaturization and improved performance.

II. PROSPECTS FOR RYDBERG SENSORS

Overall, there are several reasons for excitement about Rydberg RF sensors. Being a quantum sensor that measures quantum phase accumulation of an atomic state, they are expected to surpass several foundational limitations to traditional receivers. First, the Rydberg state’s response is linked to fundamental constants and is easily calculated to high accuracy, meaning the receiver can serve as an absolute calibration over a large, technologically-relevant parameter space, for frequencies from DC up to 1 THz. Second, active quantum sensors may achieve high bandwidths independent of the carrier frequency and are not, in general, subject to the bandwidth limitations of passive receivers using resonant electrically-small antennas. Third, and arguably most exciting, is the possibility to avoid internal thermal (Johnson) noise, even at room temperature. This is possible since the Rydberg sensor relies on measuring the atoms’ quantized internal states with low-entropy laser beams.

These aspects and overall performance of Rydberg RF sensors have been explored in increasing depth in recent years. Several key experiments identified the usefulness of Rydberg atoms for electric field sensing. Recent demonstrations have observed high precision for electric field calibration, terahertz imaging, sensing very strong fields, proof-of-principle communication reception, operation at low frequencies, and entanglement-enhanced E-field sensing. Perhaps the most seminal achievement of the decade used a beam of Rydberg atoms traversing a superconducting microwave cavity to create and stabilize non-classical states of light.

Despite this rapidly increasing, and exciting, body of work, additional advances in Rydberg sensor performance are required before they become useful as state-of-the-art, RF receivers. For one, prior works have been confined to frequencies near resonant transitions between Rydberg states. While there are hundreds of these po-
tential transitions, they are unevenly distributed between \( \sim 1 \) and 1000 GHz with highly variable sensitivity [1]. Using all of the available transitions requires a high-power laser system agile enough to rapidly tune over multiple nanometers while maintaining narrow linewidth and high precision frequency stabilization to atomic transitions. Further, previous room temperature experiments have only been sensitive enough to detect transmitted RF fields that are significantly stronger than most real-world signals. This is partially because current free-space sensors have inherently weak coupling to incoming RF and microwave modes, and a sensing area that is significantly smaller than the diffraction limit (order \( \lambda^2 \)) in most cases. Even demonstrations with decent electric field sensitivity have detected signals from RF transmitters that were driven with relatively high power at their input and/or from horns a few centimeters away from the sensing volume. Though several other recent experiments have placed thermal Rydberg atoms near RF and microwave structures for sensing purposes, wideband operation and RF power sensitivity were not directly reported [18–21]. Taken together, these realities have made it difficult to realize a continuous, wideband Rydberg sensor of weak RF fields.

To alleviate the poor coupling of free space devices, our system receives electric fields into a planar microwave waveguide that concentrates the electric field into a sub-wavelength region. Rydberg atoms are created and probed directly over the gap between a signal trace and ground plane, where the evanescent RF mode is approximately matched to the size of the optical beams (Fig. 1(c)). While the evanescent electric field dis-
splitting of Rydberg Zeeman sublevels, and/or interactions with other states in the Rydberg manifold. Future work will be required to understand what further sensitivity gains may be realized using RF heterodyne.

We also plot Sensitivity using preamplification. On the low-frequency half of the plot (red), we consider two stages of gain using Minicircuits ZFL-1000LN amplifiers, and on the high frequency half (orange), two Minicircuits ZVA-213-S amplifiers [24]. The resulting Sensitivity is calculated by input referring the intrinsic noise (green) and combining with the input noise of the preamplifiers. This improves Sensitivity by more than 40 dB beyond the directly observed Sensitivity. More advanced/optimized preamplification schemes are also possible that would allow the system to reach the thermal noise limit of the amplifiers at approximately $-171$ dBm/Hz.

We plot the theoretically modelled intrinsic Sensitivity of the device as a purple line in Fig. 1(d). The theory is calculated using a Floquet analysis that calculates the Rydberg response to an arbitrary RF electric field $\mathbf{E}$. The input RF LO and Signal powers are combined with a finite-element calculation using COMSOL Multiphysics modelling software, to determine the electric field at the location of the atoms for an applied voltage (see Appendices [D] and [E] for details). We determine Sensitivity from
one key advantage of the Rydberg sensor is that RF power may be measured dispersively, i.e. not absorbed into the atoms. A technical advantage of this is that the sensor can exhibit extremely high dynamic range and is not adversely affected by high input power or DC offsets (contrary to most sensitive spectrum analyzers). Recent work has demonstrated using Rydberg atoms to detect local electric fields of over 5 kV/m.

We demonstrate the sensor’s high dynamic range by measuring the Signal-to-Noise Ratio (SNR) as a function of the input Signal power, $P_{in}$. Figure 3(a) plots the PSN-limited SNR of the sensor as a function of signal input power for a 2 GHz signal. The LO power is constant for this data (3.9 dBm at the waveguide input), with $\delta = 700$ kHz and the signal response is linear over an input power from $-85$ dBm to $-5$ dBm. This data was measured in a 1 Hz bandwidth and the results are consistent with sensitivity measurements taken at higher bandwidths up to 1 MHz.

SNR versus input power for a resonant signal of $f_{LO} = 10.2233$ GHz, $\delta = 700$ kHz, and $-36$ dBm of LO power at the waveguide input is shown in Fig. 3(b). A similar dynamic range is observed. It is again worth reiterating that there is no nearby damage threshold for the apparatus or point where the system physics changes dramatically. By adjusting optical detunings, higher dynamic ranges are feasible. The data in Fig. 3(b) confirms the PSN-limited input Sensitivity of $-120(2)$ dBm/Hz ($-101(2)$ dBm/Hz directly measured) [25]. Figure 3(c) is a measurement of the sensor response (normalized to 1) as a function of detuning $\delta$. The 3 dB instantaneous bandwidth is 4.0 MHz, governed by the EIT bandwidth [10]. This bandwidth is independent of carrier frequency, and may be improved in the future with alternative readout schemes.

IV. SENSING AMBIENT SIGNALS

The increased sensitivity and wide tuning range allows us to detect ambient RF signals in multiple bands inside our lab using a standard rabbit ears antenna connected to the Rydberg receiver. At each LO frequency, $f_{LO}$, we sample data directly from the optical readout and record the resulting spectra. In Fig. 4 we show the spectra from measurements in the AM, FM and 2.4 GHz Industrial, Scientific, and Medical (ISM) bands. For the AM and FM bands, we attached the antenna to the inside of an outward facing window and connected it to the input of
FIG. 4. RF signals observed inside the lab building using a rabbit-ears antenna. We tune the LO to $f_{LO} = 2$ MHz, $98.4$ MHz, and $2.409$ GHz to observe AM radio stations, FM radio stations, WLAN, and Bluetooth signals. (a) AM radio stations sampled around $2$ MHz. The doubled LO is directly observed at $4$ MHz, since $f_{LO}$ is within the instantaneous bandwidth. Other large peaks are spurious signals from lab equipment. (b) FM stations sampled instantaneously around $98.4$ MHz. (c) WLAN and Bluetooth signals detected over the course of several minutes around $2.409$ GHz. The data was sampled in a max-hold configuration, showing packets sent over many WLAN subchannels (black ticks) and Bluetooth bands (highlighted in green).

V. MICROWAVE DETECTION OF RYDBERG ATOMS

The atom-circuit coupling is large enough in this experiment to directly detect the presence of the Rydberg atoms by weakly interrogating the microwave waveguide. This demonstration is an initial step to extending the seminal work of microwave-Rydberg quantum electrodynamics [16] to the room-temperature regime. Further, Rydberg-waveguide readout will be a useful tool for future sensor iterations. For one, direct microwave readout of Rydberg populations is not sensitive to Doppler shifts that plague current optical readout schemes. Second, strong collective coupling between the Rydberg ensemble and the microwave circuit may lead to a number of impactful experimental possibilities, such as quantum frequency conversion between optical and RF signals, entanglement generation, and/or Rydberg masers.

To observe the Rydberg-circuit coupling, we construct an additional microwave homodyne setup, shown in Figure 5(a), to precisely detect the phase of the output microwave signal $S_{\text{out}}$ (that were simply terminated in the previous measurements). The atom-induced microwave phase can be readily observed by sweeping the probe laser detuning (Fig. 5(b)) across the dipole-allowed Rydberg transition at $10.2233$ GHz. The atoms present a $3 \text{ mrad}$ deflection (green points) on resonance, yielding a Lorentzian-shaped signal (green fit). By tuning the microwave homodyne detection to the amplitude-sensitive quadrature, we confirm that the Rydberg atoms do not significantly absorb the microwaves (blue points of Figs. 5(b-c)). The percent amplitude deviation of the homodyne signal, relative to the total homodyne fringe height in both quadratures, is shown on the right axis. The measurements of Fig. 5 indicate weak coupling.
FIG. 5. Microwave readout of Rydberg atoms. (a) Circuit diagram for microwave homodyne detection at 10.223 GHz. (b) Amplitude (blue) and phase (green) measurements of the microwaves transmitted through the chamber, versus probe detuning. The 3 mrad phase deflection, lorentzian about Rydberg resonance, indicates the presence of Rydberg atoms. The lack of signal in the amplitude measurement indicates the Rydberg atoms do not absorb the field. (c) Zoomed view of the amplitude data in (b).

However, future room-temperature experiments should be expected to reach collective cooperativity greater than 1.

VI. DISCUSSION

Our results achieve an increased performance level for thermal Rydberg sensors, demonstrating continuous operation over a large frequency range and detecting weak, real-world RF signals. But the experiment and data also point a clear direction for further improvements. Circuit-atom coupling may be improved with a lower dielectric substrate, more sophisticated waveguide design, or a tunable resonant circuit. These improvements would increase the electric field strength above the planar surface, increasing the RF-atom coupling. However, one clear advantage of the current non-resonant design is the ease of wideband operation, which would be lost in a resonant design.

Using appropriate preamplifiers, the present experimental configuration can match the sensitivity of standard spectrum analyzers and receivers, with small positive noise figure. However, we re-emphasize that with continuing effort, the Rydberg platform may be expected to significantly outperform most wideband RF sensors, with no preamp. Such a system would be characterized by an internal noise temperature that is lower than the ambient temperature, without the use of cryogenics.

The current experimental configuration also allows us to leverage the benefits of standard antennas when measuring ambient signal fields. Most prior work with Rydberg sensors has focused on using the atoms in free space. While this has several advantages (e.g., absolute accuracy, THz frequency detection, and low field perturbation), these sensors suffer from poor coupling to any particular RF mode, and the spectral response cannot be easily tuned or narrowed. By instead in-coupling with an external antenna we are able to select a well-defined RF mode, utilizing the antenna’s spectral selectivity and gain. In this paradigm, the Rydberg sensor replaces the back-end of a receiver system, providing readout that can beat thermal Johnson noise limits and ease some impedance matching issues of traditional electronic sensors.

In parallel to increasing the RF-atom coupling, another critical area of research is to study alternate probing schemes for the thermal Rydberg atoms. It is now well established that the common, continuous electromagnetically induced transparency (EIT) method has numerous limitations relative to the standard quantum limit (SQL) for an ideal quantum sensor. With better probing schemes, several orders of magnitude in sensitivity and bandwidth may be gained. Additionally, adding a build-up cavity to recycle power in the currently expensive 480 nm laser may be a route to improved performance and/or lower cost and size.

It is an exciting prospect for Rydberg RF sensors to become a useful piece of technology in the near future. We must highlight that other physical platforms, such as electro-optics, acousto-optics, optomechanics, and other photonic platforms are making corresponding advances. In the longer term, Rydberg quantum sensors may be optimally suited to provide a full merger of classical and quantum communications. Current experiments to achieve quantum frequency conversion and coupling of Rydberg atoms to superconducting resonators, are also leading in this important direction. Much foundational study is still required to discern how these quantum tools will mature to solve real-world problems.

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Appendix A: Experimental details

For data presented, the atom chamber was heated to approximately 50 °C, with higher temperatures leading to large optical depth, and decrease sensitivity. The measured optical depth of the ensemble at the \( F = 3 \rightarrow F' = 4 \) \(^{85}\text{Rb} \) D2 transition was 2.4. The optical homodyne readout in our experiment is the same as that described in Ref. \([1]\). Overall path length fluctuations in the homodyne are detected and stabilized using a colinear off-resonant beam, that is measured in heterodyne simultaneously with the balanced photodetector (Fig. \([1]\)). The path is actively stabilized using an electro-optic modulator and a phase lock. The optical powers are actively stabilized using acousto-optic modulators.

The 480 nm laser is Pound-Drever-Hall locked to a stable reference cavity. The Rydberg coupling beam has a 1/e\(^2\) beam diameter of 380 µm and a typical power of \( \sim 500 \text{ mW} \) at the atoms’ location. The 780 nm probe laser has a 1/e\(^2\) beam diameter of 410 µm and is offset phase locked to a separate “master” laser referenced to rubidium spectroscopy. For most of the presented data, the total power in the optical homodyne/heterodyne probing beam was 67 µW with 17% of the power in the homodyne sideband (11.6 µW). The optical LO power (not to be confused with the RF LO) was 2.0 mW. The data of Figures \([3\text{ and }4]\) used a total power of 22.3 µW (3.9 µW in the probing sideband) and an optical LO power of 1 mW. For the microwave homodyne measurements in Figure \([5]\) the optical probe sidebands were turned off and the carrier frequency was moved to the probing resonance. The probing power was 4.5 µW.

Appendix B: Resonant and Off-Resonant Rydberg Response

The response of the Rydberg sensor to arbitrary RF frequencies is described in detail in Reference \([1]\). Here we provide a brief summary.

Far from resonance, the Stark shift of the target Rydberg state (i.e. the optically probed Rydberg state) depends on the atomic polarizability:

\[
\Omega_{\text{off-res}} = -\frac{1}{2} \alpha \langle E^2 \rangle_{\tau}
\]

and is proportional to the rms of the square of the total field amplitude. In this Article, we optically address the \( |59D_{5/2}\rangle \) Rydberg state in rubidium 85. For quasi-DC fields, the polarizability of this state is \( \alpha = 727.7 \text{ MHz cm}^2/\text{V}^2 \) \([8]\).

Near a resonance, the Stark shift takes the form of an Autler-Townes splitting:

\[
\hbar \Omega_{\text{on-res}} = \varphi \langle E \rangle_{\tau}
\]

where \( \varphi \) is the transition dipole matrix element and \( \langle E \rangle \) is the rms amplitude of the RF field. For the \( |59D_{5/2}\rangle \) to \( |60P_{3/2}\rangle \) transition at 10.223 336 GHz, \( \varphi = 2210.6 \text{ e}_a \). For the \( |59D_{5/2}\rangle \) to \( |58F_{7/2}\rangle \) transition at 11.225 754 GHz, \( \varphi = 2211.3 \text{ e}_a \).

The addition of an RF local oscillator field is an effective method for improving sensitivity of Rydberg sensors \([14, 22, 23]\), especially in the off-resonant square-law regime. Taking the Signal field as \( E_S \cos((\omega + \delta)t) \) and the LO field as \( E_{LO} \cos(\omega t - \varphi_{LO}) \), we can derive the atomic response to the Signal field, given the presence of the LO.

Far from resonance, the Rydberg sensor acts as a square-law sensor. The squared total field becomes

\[
E_{tot}^2 = E_S^2 \cos^2((\omega + \delta)t) + E_{LO}^2 \cos^2(\omega t - \varphi_{LO}) + 2E_SE_{LO} \cos((\omega + \delta)t) \cos(\omega t - \varphi_{LO})
\]

Again taking the time average with the assumption that \( \omega \gg \delta \) and \( \delta \ll \text{the instantaneous bandwidth} \) \( (2\pi f_{BW} = 1/) \), we get

\[
\langle E_{tot}^2 \rangle_{\tau} \approx \frac{E_S^2}{2} + \frac{E_{LO}^2}{2} + E_S E_{LO} \cos(\delta t + \varphi_{LO})
\]

Combined with Eq. \([B1]\), we find a beat at frequency \( \delta \) in the Stark shift that can be measured spectroscopically.

Note that the beat signal is linear in both the Signal and LO fields, meaning the Rydberg response is linear in the Signal with heterodyne gain from the LO.

Near resonance, in the Autler-Townes regime, the Rydberg sensor is linear in the field amplitude. We can find \( \langle E_{tot} \rangle \) by taking the root mean square of \( E_{tot} \) and assuming that \( E_S \ll E_{LO} \) to obtain

\[
\langle E_{tot} \rangle_{\tau} = \sqrt{\langle E_{tot}^2 \rangle_{\tau}} \approx E_{LO} \langle \cos^2(\omega t - \varphi_{LO}) \rangle + E_S \langle \cos(\delta t + \varphi_{LO}) \rangle^{1/2}
\]

Again taking the time average with the assumption that \( \omega \gg \delta \) and \( \delta \ll \text{the instantaneous bandwidth} \), we get

\[
\langle E_{tot} \rangle_{\tau} \approx \frac{E_{LO}}{\sqrt{2}} + \frac{E_S}{\sqrt{2}} \cos(\delta t + \varphi_{LO})
\]

Like the off-resonant case, there exists a beat at frequency \( \delta \) in the Stark shift, with amplitude linear in \( E_S \), that can be measured spectroscopically. Unlike the off-resonant signal, the LO field does not amplify the beat signal. The benefit to adding an LO lies in biasing the Autler-Townes splitting away from zero where the small Stark shifts cannot be resolved within the linewidth of the spectral signal.

Appendix C: Readout sensitivity

Figure \([6]\) presents a measurement of the optical homodyne phase sensitivity. The photon shot noise level is...
2 nrad/√Hz, shown in purple. The total readout sensitivity is shown in blue, including an additional $1/\sqrt{f}$ component due to laser phase noise.

These measurements were performed with no RF or Rydberg atoms and are consistent with the sensor noise when atoms and signals are present.

While the relative optical path length difference in our system is actively stabilized, our sensitivity to the probe laser phase noise is the result of unbalanced absolute path lengths between the optical probe and optical LO. Further engineering efforts to reduce this noise in the optical homodyne are readily possible by either reducing the overall size of the experiment (thereby improving the path length imbalance) and/or using a probing laser with narrower linewidth (thereby reducing the source laser phase noise).

Appendix D: Waveguide performance

The microwave waveguide circuit is constructed from Rogers 3003 dielectric, 0.060" thick with 35 µm thick copper plating on both sides. The waveguide slot is expanded at the atom location with the intent to increase the evanescent mode area to approximately match the size of the laser-induced ensemble. Further, the waveguide gaps are asymmetric, to encourage localization of the electric field lines on one side of the trace. Independent DC bias voltages are applied to the central signal trace of the waveguide and the ground plane opposite the dielectric from the waveguide. The signal trace DC bias is applied using a Bias-Tee external to the vacuum chamber on the Signal input. These bias fields are used to cancel ambient electric fields, with the backplane biased to 14.5 V and the signal trace at 2.2 V, for all data shown.

We performed finite element multiphysics modelling of the waveguide using COMSOL Multiphysics modelling software. Analysis includes s-parameters and RF fields within and above the waveguide. The modelled s-parameter, S21, for the waveguide is shown in orange on Fig. 7. Experimentally, we observed a reduction in the measured board S21 over the 7-month operational period (Feb. 2020 to Sept. 2020), presumably due to infection of rubidium into the substrate (visually evidenced by discoloration of the substrate). Initially, the measured S21 matched or slightly outperformed, the COMSOL prediction from 0 to 10 GHz. The measured S21 at the end of experiments is shown in Fig. 7 in blue. All reported Sensitivity measurements are referred to the waveguide input; we do not subtract waveguide losses to calculate the intrinsic Sensitivity.

We also use the COMSOL model to provide an empirical model of the waveguide conversion between input power and evanescent electric field amplitude over the waveguide gap in the region where the Rydberg atoms are excited. This conversion takes the form of:

$$E_{RF} = \sqrt{2P_{RL}}10^{(P_{in}+\alpha f_{RF}+\beta+\zeta)/20}$$

where $\sqrt{2P_{RL}} = 0.316$ V/m, $P_{in}$ is the input RF power at the input connector (in dBm), $\alpha f_{RF} + \beta$ is the empirical model fit from COMSOL modelling of the waveguide, and $\zeta = -14$ dB is a free parameter that accounts for degradation of the board performance relative to the COMSOL model. The fit parameters are $\alpha = 0.69(12)$ dB/GHz and $\beta = 46.4(13)$ dB. This conversion is used in the Floquet theory comparison, described in the next section.

Appendix E: Floquet theory

Predictions of the response of the Rydberg atoms to an arbitrary frequency are calculated using the Floquet theory described in Ref. 1. The output of this model produces the expected Stark shift of a spectroscopically probed Rydberg state due to the presence of an arbitrary RF field frequency and amplitude. We estimate the expected signal output by calculating the dynamic Stark shift.
shift, $\Omega_S$, due to the beating of $E_{\text{LO}}$ and $E_s$. This is converted to a beat signal by

$$\text{Output} = 20 \cdot \log_{10} \left( \frac{\Omega_S}{D\eta^2PR_L} \right) \quad (E1)$$

where $P = 1 \text{ mW}$, $R_L = 50 \Omega$, $D = \lambda_p/\lambda_s$ is the Doppler scaling factor [10], and $\eta = 2 \text{ MHz/mV}$ is a conversion factor between Stark shift and optical homodyne output voltage, as determined from the data shown in Figure 2(a)ii.

For the modelled Sensitivity, the Signal and LO powers are converted to electric field strength at the atoms using Eq. (D1). The resulting model of intrinsic Sensitivity (purple line in Fig. 1), corroborates the qualitative sensor response versus frequency.

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