Quantum sensors—qubits sensitive to external fields—have become powerful detectors for various small acoustic and electromagnetic fields. A major key to their success have been dynamical decoupling protocols which enhance sensitivity to weak oscillating (AC) signals. Currently, those methods are limited to signal frequencies below a few MHz. Here we harness a quantum-optical effect, the Mollow triplet splitting of a strongly driven two-level system, to overcome this limitation. We microscopically understand this effect as a pulsed dynamical decoupling protocol and find that it enables sensitive detection of fields close to the driven transition. Employing a nitrogen-vacancy center, we detect GHz microwave fields with a signal strength (Rabi frequency) below the current detection limit, which is set by the center's spectral linewidth $1/T_2$. Pushing detection sensitivity to the much lower $1/T_2$ limit, this scheme could enable various applications, most prominently coherent coupling to single phonons and microwave photons.
Sensitive detectors for weak radio-frequency (>100 MHz) signals of electric, magnetic, or pressure fields would shift several frontiers of physics. They could advance the exploration of phonons on the single-particle level and reveal weak microwave signals encountered in quantum information processing, biomedical imaging, or more exotically, the search for extraterrestrial intelligence.

Driven by this perspective, the past decade has seen the rise of detectors based on Rydberg atoms, superconducting quantum circuits, or optomechanical sensors. All approaches have achieved noise levels below 10 photons (noise temperatures below 100 mK), an order of magnitude better than state-of-the-art semiconductor detectors and maser amplifiers. However, this performance is only reached in sophisticated setups (Rydberg atoms) or at sub-Kelvin temperatures (optomechanics, superconductors).

Detectors based on solid state spin qubits could potentially overcome these limitations. Optically active spin qubits such as nitrogen-vacancy (NV) centers can be optically polarized, that is effectively laser cooled to a temperature of a few 10 mK, even in a substrate at higher temperature. Magnetic tuning of their spin transition enables resonant coupling to external fields at any frequency up to 100 GHz. Theory proposals suggest that single microwave phonons and photons can be coupled sufficiently strong to drive a full spin-flip within the spin coherence time $T_2$ (ms to s, depending on species and temperature).

However, radio-frequency sensing by spin qubits is currently precluded by a major roadblock. It is illustrated in the detection protocol of Fig. 1b, where an incoming signal drives the qubit transition, inducing a spin flip which is subsequently detected by readout of the spin. To drive a full spin-flip, an incoming signal has to saturate the spin transition. Therefore, the signal strength (Rabi frequency) has to exceed the inhomogeneous transition linewidth $\Delta \omega \sim 1/T_2$. Since $1/T_2$ is much broader than 10 MHz vs kHz for an NV center in a natural abundance crystal at room temperature), coupling of spins to high-frequency signals remains inefficient. As a specific example, interfacing spins to single phonons or photons (Fig. 1a) is currently precluded, since coupling would be possible within $T_2$ but remains out of reach of $T_2$.

For signal frequencies below a few MHz, dynamical decoupling protocols can break this limit (Fig. 1c). Here, the transition is driven by a strong continuous or pulsed control field (frequency $\omega_0$) to create a pair of photon-dressed qubit states, split by the driving field Rabi frequency $\Omega$.

As the key idea of this work, we note that the fully hybridized spin-photon states (the ‘Jaynes-Cummings ladder’) support another set of transitions at frequencies $\omega_0 - \Omega$, $\omega_0 + \Omega$, and $\omega_0$ (Mollow triplets), which enable coherent coupling of solid state spins to single phonons and photons. They could enable coherent coupling of solid state spins to single phonons and photons.

### Results

**Continuous wave Mollow absorption.** We demonstrate the creation of dressed states by the scheme of Fig. 2a. Here, the spin is initialized into the dressed state $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ by a $(\pi/2)_Y$ pulse (Y labeling the carrier phase). This state is locked as an eigenstate of a strong dressing field with orthogonal carrier phase $\phi_\Omega = \pi$. This state can be recovered by preparing into an orthogonal state and changing the phase of the signal to account for the different quadratures of the Mollow sidebands.

**Pulsed Mollow absorption as a sensing protocol.** We now convert Mollow absorption spectroscopy into a pulsed sensing protocol (Fig. 3a) to mitigate an important problem: the continuous wave (CW) protocol is prone to decoherence since fluctuations of the drive field power $\Omega$ directly translate into frequency noise of the dressed state transition $\omega_0 \pm \Omega$. We will see that pulsed protocols shift the frequency of the Mollow sideband absorption from $\omega_0 \pm \Omega$ to $\omega_0 \pm \pi/\tau$, $\tau$ denoting the pulse spacing as shown in Fig. 3b. Since timing ($\tau$) is controlled better than power, decoherence is reduced to the intrinsic limit set by the...
spin qubit. Importantly, absorption on these transitions will induce a spin trajectory similar to standard Rabi oscillations. This enables sensing of the absorbed field’s amplitude, effectively turning the probe into a signal field.

Conversion into a pulsed protocol is best understood from tracking the spin evolution across the sideband absorption sequence (Fig. 3a). We decompose the strong drive into a series of \(\pi\) pulses, spaced by a time \(t = \pi/\Omega\), and split the weak signal into a commensurate series of weak pulses with pulse area \(\epsilon \ll \pi\). We equally discretize its detuning of \(\Delta = \Omega\) — a continuous decrease in carrier phase into periodic inversions of its axis, that is a discrete decrease of the phase by \(\pi\) occurring with period \(\pi/\Delta\). At the resonance condition \(\Delta = \Omega\), this period matches the spacing \(t = \pi/\Omega\) of the strong drive. In this case, the weak signal is resonantly rectified in the toggling frame of the spin (Fig. 3a), analogous to the situation in low-frequency sensing. We note that discretization preserves the axes of all nodes at frequencies \(\Omega\) corresponding to slower Rabi frequencies in the CW sequence — the Mollow resonance merges with the inhomogeneously broadened transition. To verify this limit explicitly, we artificially shorten \(T_2^*\) of the NV center by averaging multiple measurements taken at different, Gaussian-distributed, frequencies of the microwave drive. Tuning decoherence by this technique, we find that sensitivity breaks down if pulses are spaced by more than \(T_2^*\) (Fig. 4c).

**Discussion**

With these insights, we are finally in a position to evaluate the sensitivity that could be reached by a microwave spin sensor. Table 1 presents a series of such estimates for three typical experimental scenarios, a single NV center at ambient temperature, a NV center at cryogenic temperature with single shot readout, and an ensemble of NV centers in a densely doped diamond. Our estimates derive from two assumptions:

1) We assume high-frequency sensing to be as robust against experimental fluctuations as low-frequency sensing, since it is based on the very same decoupling protocols. In particular, we assume that the same \(T_2^*\) time can be reached and the same number of control pulses can be applied. This
Fig. 3 Pulsed Mollow absorption spectroscopy (subfigures ordered clockwise). a The sideband transitions of the CW protocol in Fig. 2a can be understood as a dynamical decoupling protocol by dissecting the strong drive into a train of $\pi$ pulses and the probe into a train of weak pulses ($e$). The detuning $\Delta$ of the probe translates into periodic inversions of its axis, which are resonantly rectified by the strong drive. b Pulse sequence for high-frequency sensing, a direct implementation of the interpretation given in a. $\pi$ pulses at frequency $\omega_0$ emulate a strong drive to resonantly enhance a weak signal at frequency $\omega = \omega_0 + \Delta$. The pulse spacing $\tau$ incorporates the duration of a $\pi$ pulse. $\tau'$ is obtained from $\tau$ by subtracting the $\pi$ pulse duration. c Pulsed Mollow resonance, as measured on a NV center (upper plot) and simulated (lower plot). A resonance at $\Delta = \omega/\tau$ is framed by sidebands with nodes at $\Delta = \pm \omega/\tau \pm k\omega/\tau$ (with $k \in \mathbb{N}$, sequence duration $T = 2\pi n$, cycle number $n = 4$). d Linewidth of the resonance. The line narrows below the natural linewidth $1/T_2^*$ (as observed in an optically detected magnetic resonance (odmr) experiment, see also Supplementary Note 1) for sequences longer than the dephasing ($T > T_2^*$). e Simulated spectral response to sensing sequences with different decoupling protocols. The pulse spacing between 24 $\pi$ pulses was kept constant at $\tau = 127.6 \text{ ns}$. The stated effective Rabi frequencies are for Rabi oscillations driven on the Mollow resonance. ‘XY8, phase switching’ refers to the protocol of Fig. 4. More detailed discussion in Supplementary Note 4. Data traces in d, e have been shifted vertically for better comparison by an offset of 1.0. The ODMR trace in d is shifted horizontally by 2623 kHz.

assumption is justified since sensitivity characterizes the response to an infinitesimally weak signal where the spin follows a nearly identical trajectory as in the bare decoupling sequence.

2) In contrast to low-frequency sensing, $T_2$ is bounded by an upper limit of $N_{\text{max}} \cdot T_2^*$, where $N_{\text{max}} \approx 1000$ denotes the maximum number of control pulses that can be applied before pulse errors deteriorate coherence\(^1\). This condition arises from the additional constraint that pulses have to be spaced by less than $T_2^*$, as discussed in the context of Fig. 4. While this condition does not set the limit for experiments on single NV centers, where isotopic purification can push $T_2^*$ times into the range of 100 ns, it is the limiting factor for ensemble sensing where inhomogeneous broadening shortens $T_2$ times down to the sub-microsecond timescale.

More importantly, these estimates suggest that NV centers should be able to couple coherently to phonons and phonons in the scenarios of Fig. 1 within their coherence time $T_2$ (assuming the values of Table 1). This would enable detection of both particles by coherent absorption and subsequent detection of the spin state, a more powerful measurement than time-averaged detection of a signal with a mean strength on the single-particle level. It could pave the way to a quantum bus based on these signals, mediating coupling between distant spins or to other qubits. The narrow transition provided by our scheme could aid the development of room-temperature MASERs based on optically initialized spins\(^1\). Their use as amplifiers could provide another approach to sensing of weak signals, complementary to optical detection.

In summary, we have pushed spin-based quantum sensing to frequencies much higher than the available Rabi frequency $\Omega$. In the language of superconducting amplifiers, this promotes spins to phase-sensitive microwave detectors that might provide sufficient sensitivity to detect single phonons and photons. Compared to competing approaches such as Josephson parametric amplifiers, our scheme has a very narrow bandwidth. It absorbs signals only within a narrow window of width $1/T_{\text{25}}^*$ ($\approx 100 \text{ Hz} - 10 \text{ kHz}$ for NV centers) and, operated as a detector, would be limited to a maximum count rate of the same order of magnitude. It seems plausible, however, that a future extension of our experiment could continuously shift this window across frequencies up to several 100 GHz, tuning the spin transition e.g. by a magnetic field\(^1\). Crucially, the absorption frequency $\omega_0 \pm \omega/\tau$ is set only by timing and frequency of the external drive, which can be controlled well. It is independent of the native spin transition and hence resilient to drifts in surrounding fields.

From a fundamental perspective, we have provided an intuitive microscopic understanding of the Mollow triplet as a pulsed quantum protocol. It appears most intriguing to extend this novel perspective to other effects of quantum interference, such as electromagnetically induced transparency.

Methods

**NV center preparation.** All experiments have been performed on single NV centers spontaneously created inside a polycrystalline electronic grade Ila diamond during chemical vapor deposition (Element Six, part N° 145-500-0356).

**Quantum control.** Both the strong drive and the weak signal were generated by an Arbitrary Waveform Generator (Rigol DG5352), which was mixed onto a GHz frequency carrier, amplified (amplifier MiniCircuits ZHL16W-43-S+), and applied
to the NV center by a coplanar waveguide. All given microwave excitation powers refer to the input of the coplanar waveguide. They have been calculated from the output power of the Arbitrary Waveform Generator by adding a constant offset of +5 dBm to account for all gains and losses along the path.

Spin readout. The spin state was measured by fluorescence readout in a high-NA confocal microscope (excitation 532 nm, ~1 mW power, detection in the additional 650 nm band by an objective lens Olympus UPLSAPO 60 x 1.35O). In total, 4-8×10⁵ readout repetitions per trace were made, corresponding to a measurement time of 15–30 min for each trace. All sequences were recorded twice, with and without an additional π pulse before readout. The difference of both datasets was normalized to the signal contrast of a Rabi oscillation to yield a quantitative estimate of |\langle 0|\psi \rangle|^2.

Data availability. All relevant data is available from the authors upon request.

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Table 1 Sensitivity of a NV-based sensor for high-frequency signals

| Signal & Temperature | Single NV, 300 K | Single NV, < 77 K, 12C, SSR | NV Ensemble, 300 K |
|---------------------|-----------------|------------------------|-------------------|
| T2                  | 1 ms²           | 10 ms²                 | 100 μs            |
| T2                  | 2 μs            | 100 μs                 | 100 ns            |
| #Pulses             | > 500¹⁹         | > 100²⁹                | 1000³⁹            |
| #NV                 | 1               | 1                      | 10¹³²             |
| Spin detection      | 0.1%²¹          | 100%²¹                 | 0.1%²¹            |
| efficiency η        | 5 nT/√Hz⁴⁰      | 50 pT/√Hz              | 1 pT/√Hz          |

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Author contributions
T.J. and F.R. conceived the experiment. A.M.W. and T.J. developed the simulations and optimized the protocols. T.J., A.M.W., and G.B. prepared the sample and performed the experiment. T.J., A.M.W., and F.R. analyzed the data. T.J., A.M.W., and F.R. wrote the paper. All authors read and commented on the manuscript.

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