Rydberg atoms for quantum signal processing and transduction

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Continuous wideband microwave-to-optical converter based on room-temperature Rydberg atoms

Six-wave mixing upconversion

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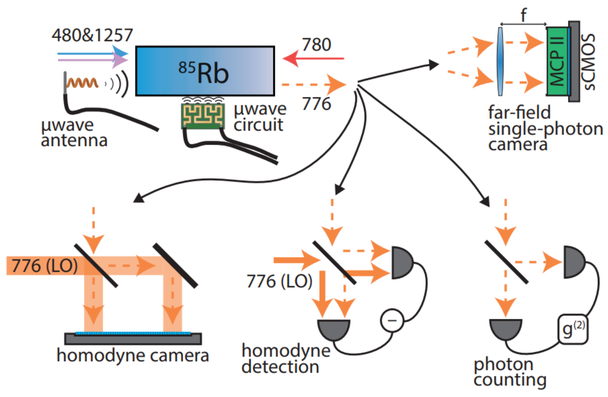
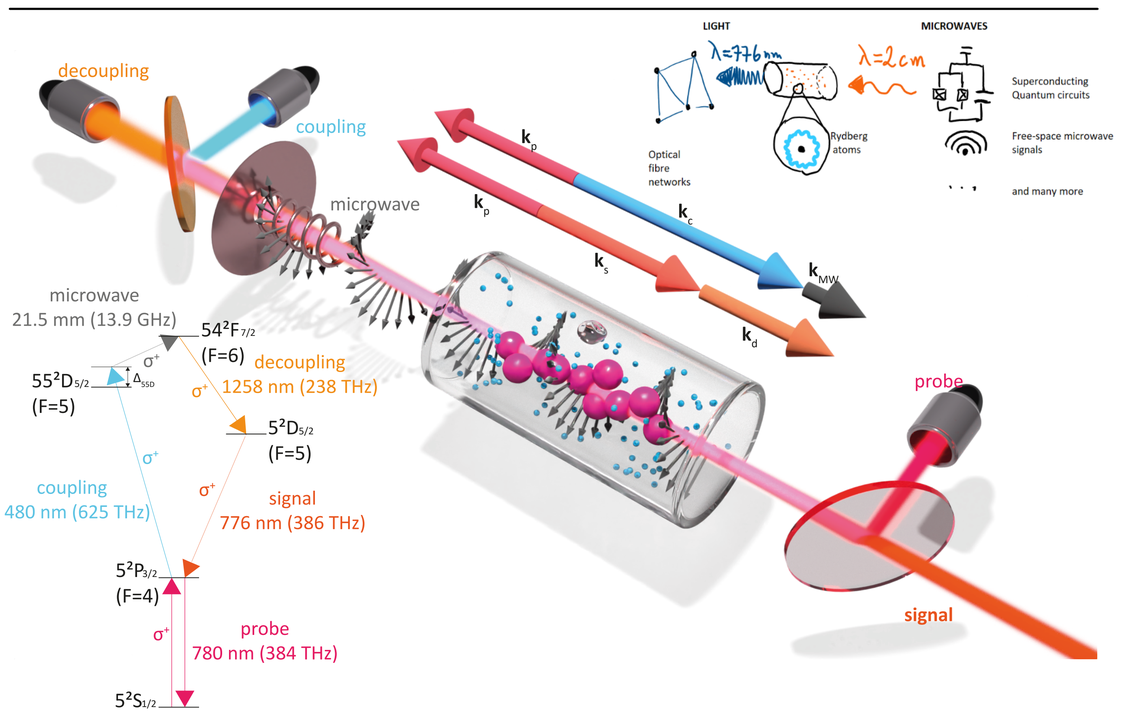
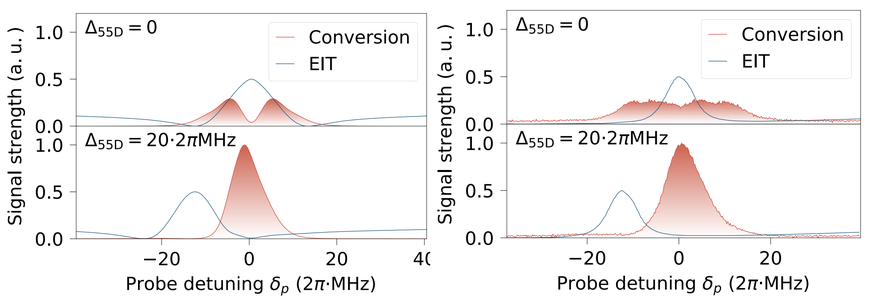
Hot-atom vapor for Rydberg sensor/converter for applicable to many scenarios

Six-wave mixing process selected to minimize noise and partially avoid Doppler broadening

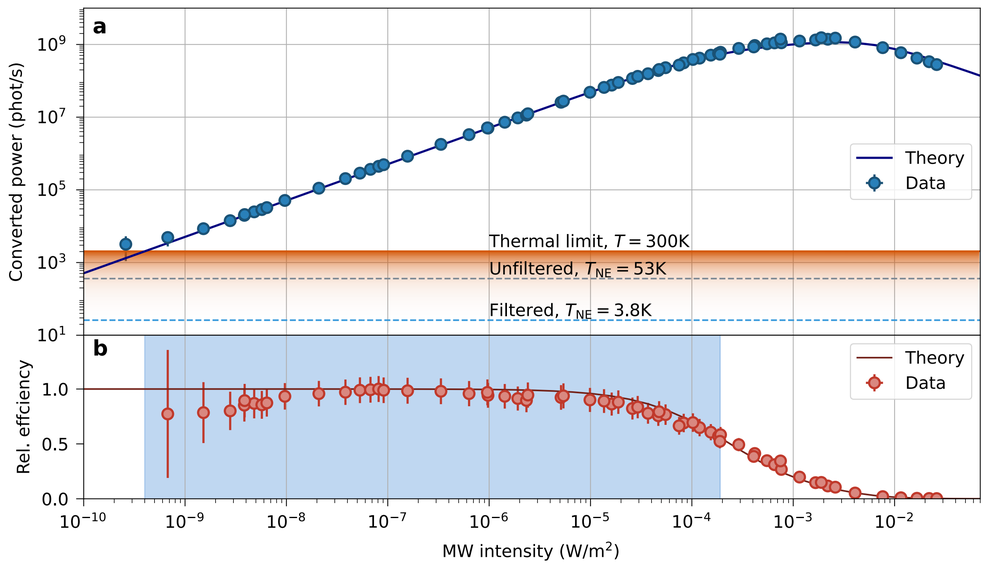






Probe scan reveals optimal conversion off-resonance wrt EIT window.
(cf. Nat. Photonics 16, 291–296 (2022))

Reaching the thermal noise



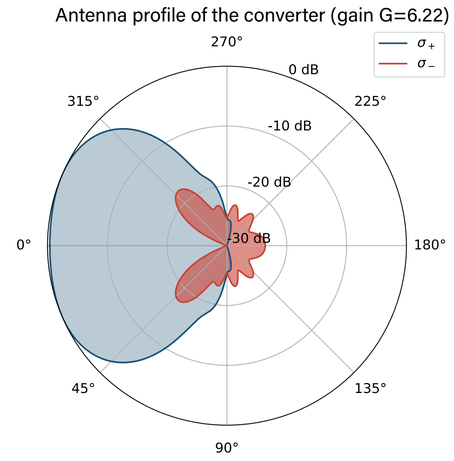
Saturation due to Autler-Townes splitting

A-T splitting also provides fundamental reference for electric field
(cf. Nature Physics 8, 819–824 (2012))

1.59 nV cm^{-1} (rad/s)$^{-1/2}$ Measured
1.64 nV cm^{-1} (rad/s)$^{-1/2}$ Calculated

Intrinsic noise (dark background almost 100 times lower than thermal radiation)

Antenna profile of the converter (gain G=6.22)



$$\langle E_{\mathrm{eff}}^2 \rangle = \frac{\omega^2 \langle \mathcal{E} \rangle}{\pi^2 c^3 \varepsilon_0} \frac{1}{4\pi} \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} \mathrm{d}\theta \sin(\theta) |\eta(\theta)|^2$$

$$\langle \mathcal{E} \rangle = \frac{\hbar\omega}{e^{\hbar\omega/k_B T} - 1},$$

$$|\eta(\theta)|^2 = \left(\cos\left(\frac{\theta}{2}\right)^4 + \sin\left(\frac{\theta}{2}\right)^4 \right) |\eta_{\mathrm{phm}}(\theta)|^2$$

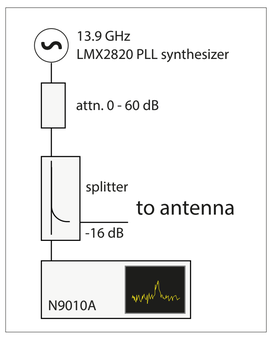
Geometry-corrected thermal noise of the electric field

$$\chi_\theta = E_p E_p^* E_c E_d^* E_{\mathrm{MW}}(\theta)$$

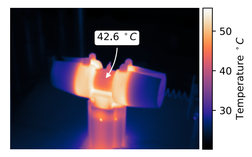
Corrections due to phase matching (including Gouy phases!)

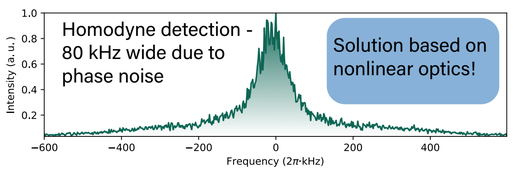
$$\eta_{\mathrm{phm}}(\theta) = \int_{-L/2}^{L/2} \mathrm{d}z \int_0^{2\pi} \mathrm{d}\phi \int_0^{\infty} \rho \mathrm{d}\rho \chi_\theta u_s^*$$

Full experimental setup

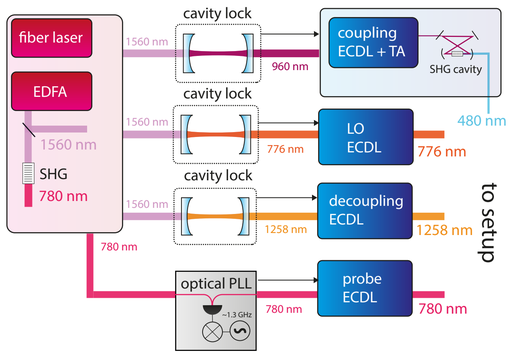


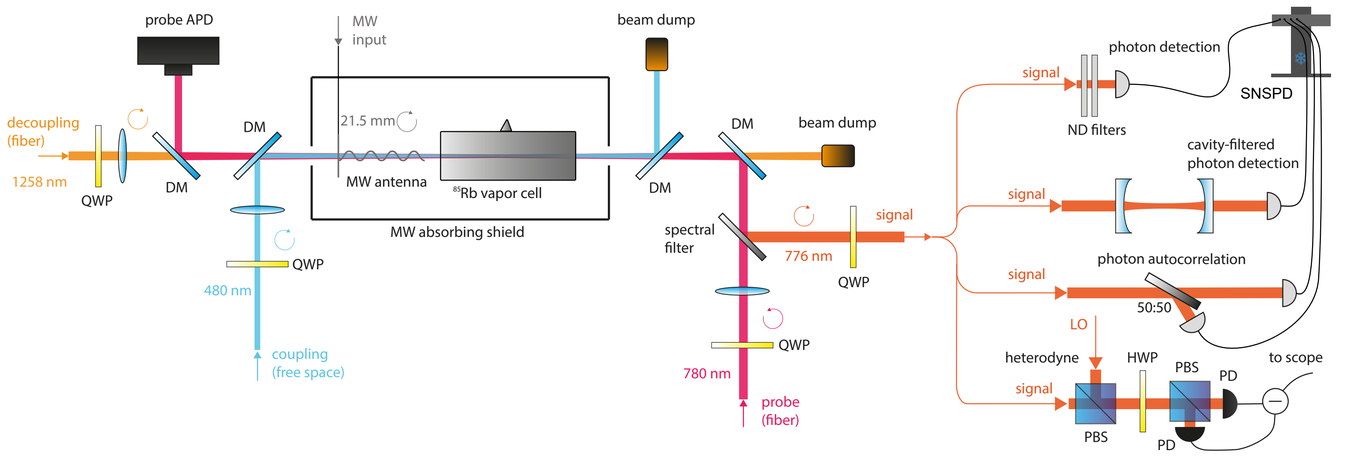
3D printed plastic heater with air-channels



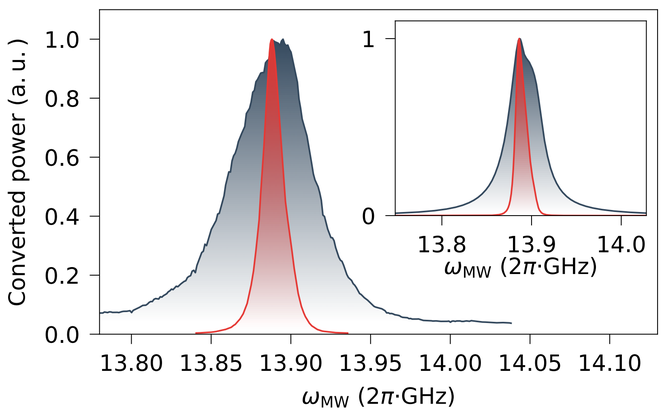


Laser system - cavity transfer locks





Spectroscopic and statistical properties



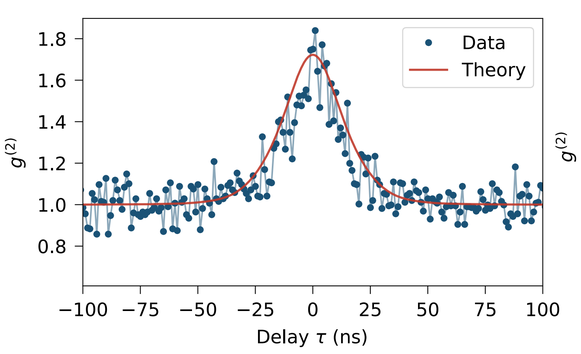
Wiener–Khinchin theorem relates spectrum and the correlation function

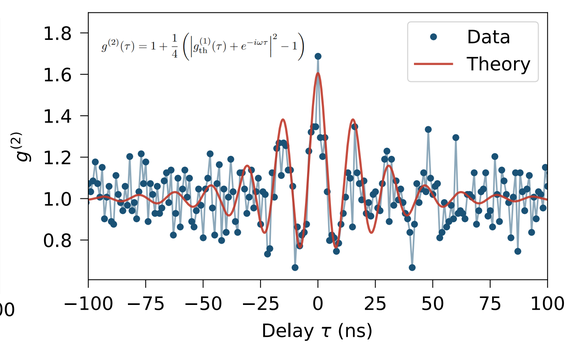
$$g_{\mathrm{th}}^{(1)}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} |S(\omega)|^2 e^{-i\omega\tau} \mathrm{d}\omega$$

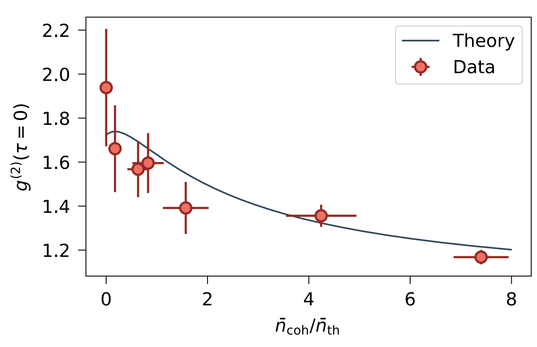
We recover the spectrum by measuring transduction function and assuming white noise properties of thermal radiation

$$g^{(2)}(\tau) = 1 + \frac{\left| \bar{n}_{\mathrm{th}} g_{\mathrm{th}}^{(1)}(\tau) + \bar{n}_{\mathrm{coh}} e^{-i\omega\tau} \right|^2 - \bar{n}_{\mathrm{coh}}^2}{\left(\bar{n}_{\mathrm{th}} + \bar{n}_{\mathrm{coh}} + \bar{n}_{\mathrm{noise}} \right)^2}$$

More generally, the second-order correlation function may contain dark noise and coherent compontents

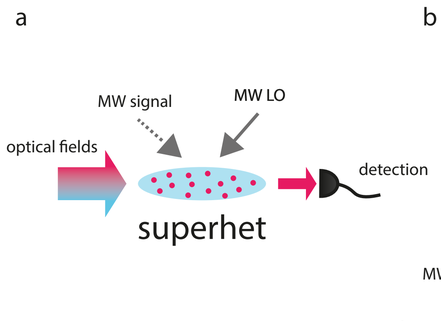


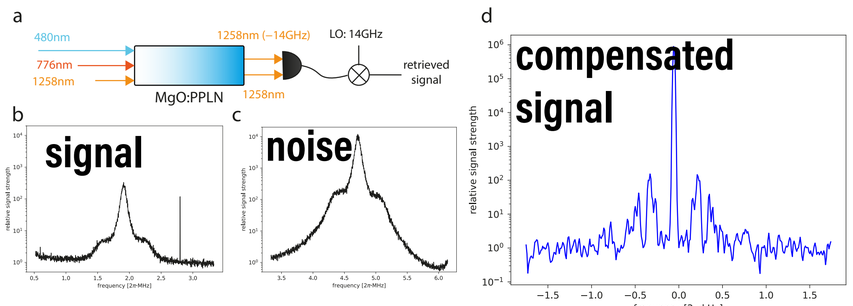


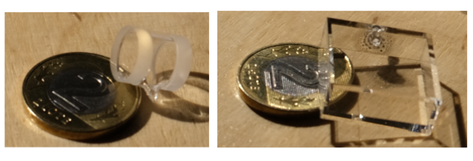


Photon counting of upconverted microwave radation:
- thermal statistics observed
- interference between coherent and thermal field
- transition between thermal and coherent statistics

Phase-sensitive & integrated all-optical sensor







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M. Parniak et al., Nature Communications 8, 2140 (2017) - multimode quantum memory based on Rb atoms
S. Borówka et al., Applied Optics 61, 8806-8812 (2022) - Rydberg-atom FM and AM microwave receiver/simple scenario but with much less sensitivity
G. Santamaria-Botello et al., arXiv:2209.00908 - comparison of noise temperatures of Rydberg-atom receivers

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