An integrated quantum phased array receiver system in silicon photonics

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Abstract: We demonstrate a quantum analog of electromagnetic phased arrays with more than 1,000 functional components integrated on a silicon photonic chip. With an array of 32 metamaterial antennas and 32 quantum-limited coherent receivers employing homodyne detection, we perform imaging, beamforming and beamsteering with squeezed light over free space.

1. Introduction

Free-space interfaced systems enable various applications such as RADAR, LiDAR, remote sensing and wireless communications. In many free-space links, phased arrays – coherent arrays of antenna elements that can receive or transmit electromagnetic waves – are used to enable spatiotemporally configurable signal reception or transmission with high signal gain [1, 2]. While antenna arrays are ubiquitous in free-space links, all previous developments in antenna arrays have been achieved only with classical states of light. We generalize the operating principles of antenna arrays to quantum states of light with the concept we refer to as "quantum phased arrays." As a proof-of-concept, we demonstrate a 32-channel silicon photonic-electronic system that provides a low-loss, low-noise and scalable free-space-to-chip interface for non-classical light.

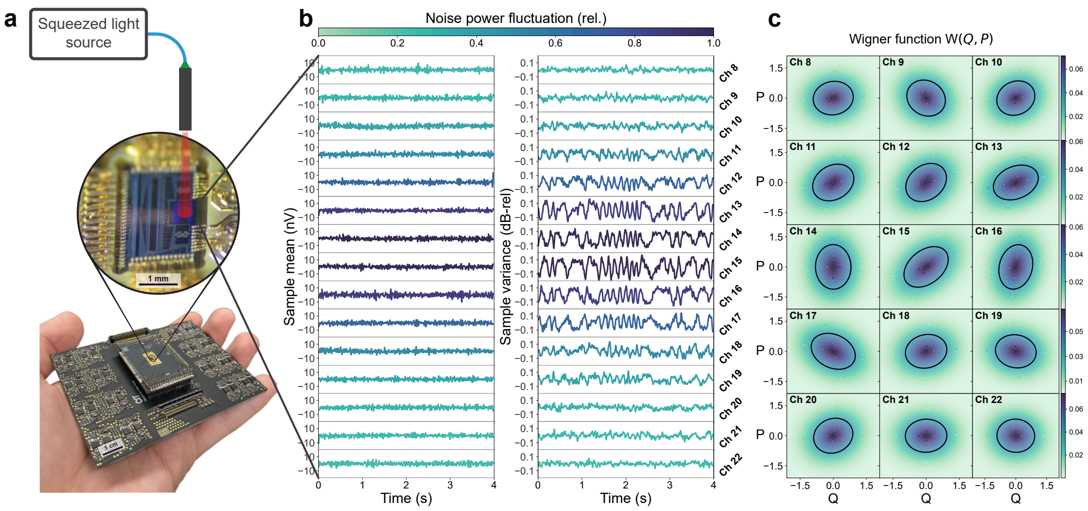

Fig. 1: Quantum coherent imager. **a)** Image of the QPA photonic integrated circuit (PIC) packaged with electronics while a squeezed light beam is illuminating the aperture. The PIC is wirebonded to an interposer, which is plugged into a motherboard that hosts a 32-channel TIA array and the CMRR auto-correction circuit. **b)** Sample means and variances of the output voltages of the middle 15 channels over time, showing the quadrature variance fluctuations of squeezed vacuum as LO phase is modulated. **c)** Corresponding Wigner functions of the 15 pixel modes reconstructed from sample means and variances.

2. Quantum phased array system

The quantum phased array (QPA) system consists of 32 channels hosting 32 metamaterial antennas (MMAs) followed by 32 quantum-limited coherent receivers (QRXs) employing homodyne detection [3]. The 32 MMAs form a large active area aperture with more than 500,000 sub-wavelength-engineered grating elements over 550 × 550 μm^2 footprint. Each MMA has a measured geometric loss of 1.14 dB with 200 μm diameter collimated beam incident on the aperture and a measured insertion loss of 3.82 dB dominated by downward scattering. Each QRX consists of a push-pull tunable Mach-Zehnder interferometer, a pair of balanced Ge photodiodes, a transimpedance amplifier (TIA), and a common-mode rejection ratio (CMRR) auto-correction circuit that corrects the imperfect CMRR of each QRX due to fabrication variations. The QRXs achieve an insertion loss of 1.58 dB, a shot noise clearance of 30.3 dB, a CMRR of 90.2 dB, an local oscillator (LO) power knee of 12.6 μW, a 3-dB bandwidth of 10.4 MHz and a shot-noise-limited bandwidth of 381 MHz [3]. Since the on-chip photodiodes have $>$20 GHz bandwidth, replacing the TIA with a higher bandwidth but lower shot noise clearance TIA allows us to achieve a 3-dB bandwidth of 2.57 GHz and a shot-noise-limited bandwidth of 3.70 GHz [4].

3. Squeezed light imaging

First, we operate the QPA system as a quantum coherent imager. Coherent light from a fiber-coupled continuous wave laser at a 1550 nm wavelength is split into a signal and LO path. Light from the signal path is used to generate squeezed vacuum with Type 0 spontaneous parametric downconversion, and light from the LO path is distributed to all 32 QRXs [3]. The squeezed light is transmitted to the chip with a fiber collimator, which transmits a collimated Gaussian beam with a beam diameter of 200 μm. The squeezed light incident to the QPA aperture is distributed over the 32 MMAs, and the light coupled onto each antenna is measured by a QRX. The output voltage of each QRX is proportional to the phase-dependent quadrature of its pixel mode, allowing for the construction of a phase-sensitive 32-pixel image of the incident field quadratures (Fig. 1b) and the corresponding reconstructed Wigner functions (Fig. 1c).

4. Beamforming and beamsteering

Next, we operate the system as a quantum phased array receiver (Fig 2a.). Squeezed light is transmitted with the fiber collimator to the QPA over free space and the radio-frequency (RF) outputs of all 32 QRXs are coherently combined with an RF power combiner. On-chip LO phase shifters are calibrated to beamform on squeezed light transmitted to the QPA at a given angle of incidence. For 32 combined channels, the spatial selectivity of the reception beam is characterized for squeezed light transmitted to the chip at normal incidence to the aperture, yielding a 3 dB (50% efficiency) beamwidth of 0.20±0.02 degrees (Fig 2b.). The field of view of the QPA is characterized by transmitting squeezed light over multiple angles and beamforming at each angle, yielding a 3 dB field of view of 2.66±0.25 degrees (Fig 2c.).

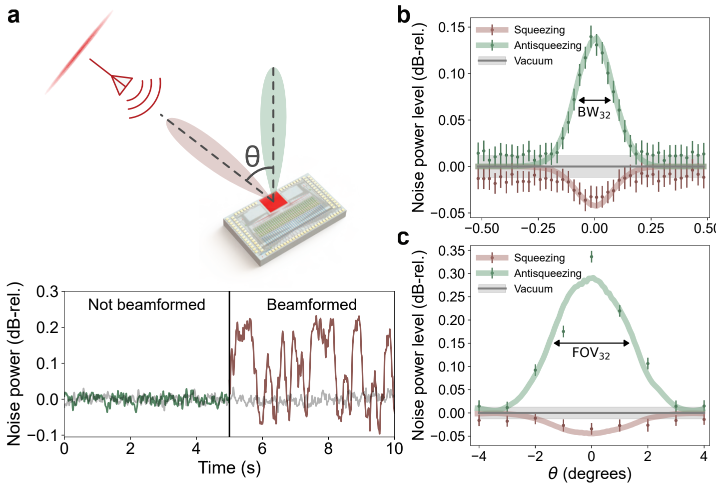

Fig. 2: Quantum phased array receiver. a) Demonstration of beamforming with squeezed light, showing non-classical signal only when QPA is beamformed at a squeezed light transmitter. **b)** Beamwidth characterization with squeezed light for 32 channels combined. **c)** Field of view characterization with squeezed light for 32 channels combined.

5. Conclusion

We present the first demonstration of a quantum phased array, which generalizes the operating principles of antenna arrays to quantum states of light, in a large-scale silicon photonic-electronic system with more than 1,000 functional components on chip. With our novel squeezed light imaging and beamforming demonstrations, we report the first detection of squeezed light with a 32-channel array of on-chip homodyne detectors and the first directional free-space-to-chip interface for non-classical light with a metamaterial aperture [3]. Together with a transmitter counterpart to our system, our approach could enable wireless quantum technologies based on QPA transceivers such as free-space quantum sensors and wireless quantum communication networks.

References

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