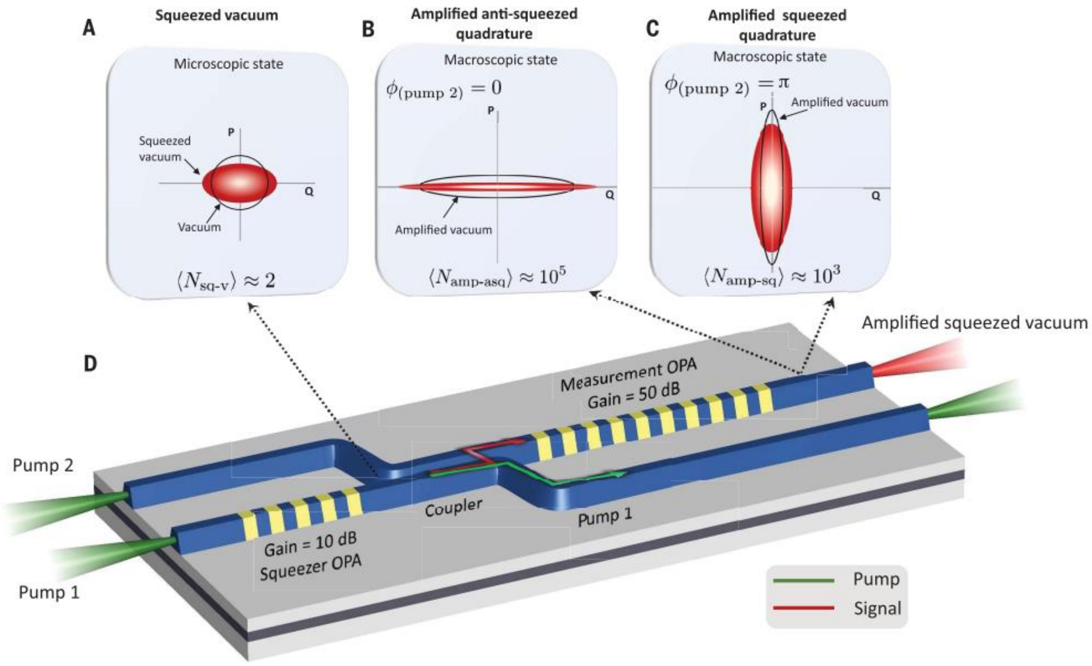
Few-cycle vacuum squeezing in nanophotonics



Quantum information processing offers great promise for computation, secure communication, metrology, and sensing. Many physical platforms such as nuclear spins, superconducting circuits, photonics, trapped ions, quantum dots, and neutral atoms have widely been explored in the pursuit to build quantum information processors (1). Among these, photonics stands out because of its potential for scalability, room-temperature logical operations, and ease of encoding quantum information in both discrete and continuous variables (2).

量子信息处理为计算、安全通信、计量和传感提供了巨大的希望。许多物理平台，如核自旋、超导电路、光子学、囚禁离子、量子点和中性原子，都已被广泛探索，以构建量子信息处理器（1）。其中，光子学因其潜在的可扩展性、室温逻辑操作以及易于在离散变量和连续变量中编码量子信息而脱颖而出（2）。

In continuous-variable (CV) quantum photonics, information is encoded in continuous amplitude and phase values of the quantized electromagnetic field. The single-mode and multimode squeezed states are widely used for various applications, including quantumenhanced interferometry such as in the Laser Interferometer Gravitational-Wave Observatory (3), microscopy (4), and quantum teleportation (5). Moreover, highly entangled CV quantum states, that is, cluster states (6–8), serve as a universal resource for one-way quantum computation.

在连续变量量子光子学中，信息以量子化电磁场的连续振幅和相位值编码。单模和多模压缩态广泛用于各种应用，包括量子增强干涉术，如激光干涉仪重力波观测台（3）、显微镜（4）和量子隐形传态（5）。此外，高度纠缠的CV量子态，即簇态（6-8），是单向量子计算的通用资源。

Typically, such high-quality CV states are generated from a single- or two-mode squeezed vacuum produced using quadratic [c(2)] parametric processes either in bulk crystals or waveguides with large (~10 to 100 mm2) mode areas (6–10). Although such experiments using bulky discrete components have been successful in demonstrating small- and medium-scale quantum circuits, it is desirable to achieve CV quantum states with comparable qualities in nanophotonics to enable large-scale integrated quantum circuits.

通常，这种高质量的 CV 态是由在大块晶体或波导中使用二次[c（2）]参数过程产生的单模或双模压缩真空产生的(~10 至 100 mm2）模式面积（6–10）。尽管使用体积庞大的分立元件进行的此类实验已成功地演示了中小型量子电路,但希望在纳米光子学中实现具有类似质量的 CV 量子态，以实现大规模集成量子电路。

In nanophotonics, silicon nitride (SiN) and silica platforms have been used for many quantum photonic experiments, such as entangled photon-pair generation, squeezing, error correction, and small-scale Gaussian boson sampling (11–13). However, their inherently weak cubic [c(3)] nonlinearity typically necessitates using high–quality factor resonators, which imposes limitations on accessible squeezing levels and bandwidths. Despite advances, the measured squeezing levels have so far remained around 2 dB in nanophotonics (see supplementary materials, section 8).

在纳米光子学中，氮化硅（SiN）和二氧化硅平台已用于许多量子光子实验，例如纠缠光子对的产生、压缩、误差校正和小尺度高斯玻色子采样（11–13）。然而，它们固有的弱立方[c（3）]非线性通常需要使用高质量因子谐振器，这对可获得的压缩电平和带宽造成了限制。尽管取得了进步，但在纳米光子学中，迄今为止测量到的压缩能级仍保持在 2 dB 左右（见补充材料，第 8 节）。

On the other hand, the measurements in CV quantum systems have typically relied on balanced homodyne detection using highly efficient and low-noise photodetectors, which are limited to bandwidths in the mega- to gigahertz range (14). Moreover, in nanophotonics, the loss associated with transferring the microscopic quantum states from a tightly confined mode to a photodetector has imposed barriers in the measurement capabilities of such states (15–17). A potential solution for these measurement challenges lies in all-optical measurement schemes based on a noiseless phase-sensitive amplifier with sufficiently large gain (18–21) that can eliminate the bandwidth limitations of homodyne detection and the sensitivity to detection losses. However, achieving such large gains (>30 dB) over broad optical bandwidths is challenging in nanophotonics with cubic nonlinearity (22). Such an all-optical measurement allows one to exploit the entire optical bandwidth of quantum fields and thereby paves a practical path toward ultrafast all-optical CV quantum information processors using time- and frequencymultiplexed schemes (6–8).

另一方面，CV 量子系统中的测量通常依赖于使用高效低噪声光电探测器的平衡零差检测，这些探测器仅限于兆赫到千兆赫兹范围内的带宽（14）。此外，在纳米光子学中，与将微观量子态从紧束缚模式转移到光电探测器相关的损耗对此类态的测量能力造成了障碍（15-17）。这些测量挑战的潜在解决方案在于基于无噪声相敏放大器的全光测量方案,该放大器具有足够大的增益（18-21），可以消除零差检测的带宽限制和对检测损耗的灵敏度。然而，在具有立方非线性的纳米光子学中,在宽光学带宽上实现如此大的增益(>30 dB)是一项挑战(22)。这种全光测量允许人们利用量子场的整个光学带宽,从而为使用时间和频率复用方案的超快全光 CV 量子信息处理器铺平了一条切实可行的道路（6-8）。

Recently, lithium niobate (LN) nanophotonics has opened promising avenues in optical communication, sensing, and computation owing to its extraordinary optical, electrical, and acoustic properties (23). A combination of subwavelength confinement of the optical mode, strong c(2) nonlinearity, high-fidelity quasi-phase-matching by periodic poling, and dispersion engineering for longer interaction lengths has enabled devices outperforming the traditional LN devices (24–26).

最近，铌酸锂（LN）纳米光子学由于其非凡的光学、电学和声学特性，在光通信、传感和计算方面开辟了有希望的途径（23）。光学模式的亚波长限制、强 c（2）非线性、通过周期极化实现的高保真准相位匹配以及更长相互作用长度的色散工程，使得器件的性能优于传统 LN 器件（24–26）。

In this work, we used a nanophotonic circuit in LN to experimentally demonstrate the generation and all-optical measurement of an ultra-short-pulse squeezed vacuum as the building block of scalable CV quantum nanophotonics. Our circuit combines two dispersionengineered phase-sensitive optical parametric amplifiers (OPAs) (24) (Fig. 1). The first OPA generates a microscopic squeezed vacuum, which is then amplified with a high-gain OPA to macroscopic levels within the same nanophotonic chip. The resulting macroscopic field carries information about the microscopic squeezed state, which can be measured with a high tolerance to loss.

在这项工作中，我们使用 LN 中的纳米光子电路来实验演示超短脉冲压缩真空的产生和全光测量，作为可缩放 CV 量子纳米光子的构建块。我们的电路结合了两个分散设计的相敏光参量放大器（OPA）（24）（图 1）。第一个 OPA 产生微观压缩真空，然后用高增益 OPA 将其放

大到同一纳米光子芯片内的宏观水平。由此产生的宏观场携带有关微观压缩态的信息，可以用高容限损耗测量微观压缩态。

We have demonstrated few-cycle vacuum squeezing and its all-optical measurements in the LN nanophotonic platform. Our on-chip all-optical loss-tolerant broadband measurements through high-gain phase-sensitive amplification enabled squeezing measurements over more than 25 THz of bandwidth while providing measurement purification against the detection losses as high as Loffchip overall ∼ 7 dB. Combined with the recent advances such as high-speed electro-optic modulators and integrated single-photon detectors (23), we envision that our results may enable scalable ultrafast all-optical quantum information processors in LN nanophotonic platform.

我们在 LN 纳米光子平台上演示了少周期真空压缩及其全光测量。我们通过高增益相敏放大实现的片上全光容损宽带测量，能够在超过 25 THz 的带宽上压缩测量，同时针对高达 Loffchip 整体的检测损耗提供测量净化∼ 7 分贝。结合高速电光调制器和集成单光子探测器（23）等最新进展，我们设想我们的结果可以在 LN 纳米光子平台上实现可扩展的超快全光量子信息处理器。