

Ultra-Large Cross-Phase Modulation for Room-Temperature Photon-Number-Resolving Detection

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Abstract: We propose and analyze a room-temperature photon-number-resolving detection scheme based on cascaded sum-frequency generation. We measure an effective $|n_2|$ of 6×10^{-12} cm^2/W in lithium niobate, which is 600x larger than the intrinsic value.

Photon number resolving (PNR) detection represents a critical capability for many quantum computing and metrology applications, including type-I fusion gates, non-Gaussian state generation, and Boson sampling. State-of-the-art PNR detectors are based on superconducting effects that operate at cryogenic temperatures. Nevertheless, most quantum photonic devices operate at room temperature due to the excellent coherence properties of photons. A room-temperature on-chip PNR detector would greatly reduce the size and cost of quantum photonic systems and allow quantum technologies to be more accessible to real-world applications, such as sensing and computing acceleration. It has been shown theoretically [1-3] that PNR detection can be realized through cross-phase-modulation (XPM) and interferometric measurement [Fig. 1(a)]. However, the typical nonlinear refractive indices (n_2) of photonic materials range from 10^{-16} to 10^{-13} cm^2/W, which corresponds to a phase shift $< 10^{-8}$ m^{-1} for a 1-ns long single-photon pulse in a photonic waveguide. More importantly, the probe beam also experiences self-phase modulation (SPM) due to its own photon-number uncertainty [1], significantly increasing the detection noise floor.

Here, we demonstrate theoretically and experimentally that exceptionally large XPM can be achieved by replacing the typically used $\chi^{(3)}$ material with $\chi^{(2)}$-based periodically-poled lithium niobate (PPLN), which can impart effective XPM through cascaded sum-frequency generation (SFG) [4-5]. This replacement offers two critical improvements. First, a much larger effective nonlinear coefficient can be achieved than with standard photonic materials (e.g., silicon nitride). Second, the relative strengths of XPM and SPM depend on the phase-matching conditions and can be engineered to enhance or suppress either process. Furthermore, by using microresonators to enhance nonlinear interactions, our analysis shows that single-photon-level sensitivity can be achieved with ~ 10-MHz cavity linewidths, which are achievable with the state-of-the-art fabrication capabilities [6].

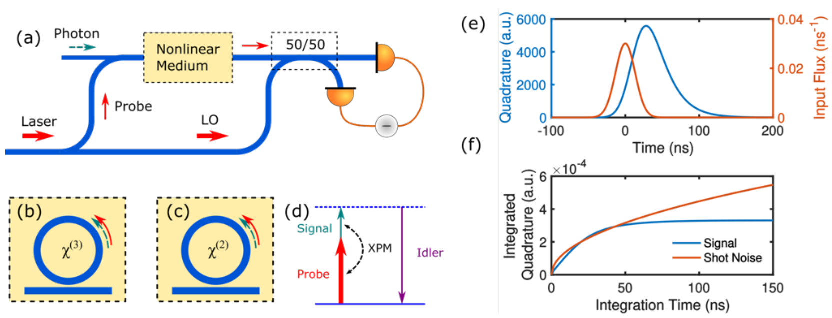

Fig. 1. (a) Measurement schematics. (b,c) Choices of nonlinear media. (d) Level diagram for the SFG process which enables effective XPM interaction. (e) Simulated input signal and time-resolved measurement outcome of proposed scheme. (f) Comparison of signal and noise strengths for different integration time.

We model the dynamics of the cavity-based SFG with the following equations:

$$\frac{d\hat{a}(t)}{dt} = -\frac{\alpha}{2}\hat{a}(t) + \kappa\hat{b}^{\dagger}(t)\hat{c}(t) - \sqrt{\alpha}A - \sqrt{\alpha}\hat{a}_{in}(t), \tag{1}$$

$$\frac{d\hat{b}(t)}{dt} = -\frac{\beta}{2}\hat{b}(t) + i\delta\hat{b}(t) + \kappa\hat{a}^{\dagger}(t)\hat{c}(t) - \sqrt{\beta}\hat{b}_{in}(t), \tag{2}$$

$$\frac{d\hat{c}(t)}{dt} = -\frac{\gamma}{2}\hat{c}(t) + i\rho\hat{c}(t) - \kappa\hat{a}(t)\hat{b}(t) - \sqrt{\gamma}\hat{c}_{in}(t), \tag{3}$$

where $\hat{a}$, $\hat{b}$, and $\hat{c}$ are the annihilation operators for probe, signal and idler modes, respectively, κ is the nonlinear coefficient, A^2 is the photon flux of the probe beam, δ and ρ are the detunings, α, β, and γ are the bus-ring coupling rates, and $\hat{a}_{\text{in}}$, $\hat{b}_{\text{in}}$, and $\hat{c}_{\text{in}}$ are annihilation operators for the incoming quantum fields. We solve Eqns. (1) – (3) using perturbation methods. For photons with a bandwidth sufficiently smaller than the ring we can derive a simplified result for the phase quadrature,

$$i\langle\hat{a}(t)-\hat{a}^{\dagger}(t)\rangle = \frac{128A\kappa^2\alpha\beta\rho}{(16\kappa^2A^2+\alpha\beta\gamma-4\alpha\delta\rho)^2+4\alpha^2(\delta\gamma+\beta\rho)^2}\langle\hat{b}_{in}{}^{\dagger}(t)\hat{b}_{in}(t)\rangle, \quad (4)$$

which represents the measurable quantity to determine the number of photons in the signal field. For small A, this quadrature value scales proportional to A which represents a constant phase shift. However, the A^2 term on the denominator indicates that the effective XPM becomes less efficient when the probe power is high. For a high-Q microresonator, this corresponds to nanowatts of power. Using a classical probe beam at (sub)nanowatt level, the measurement sensitivity is limited by shot noise, while the intrinsic SPM noise and thermal noise are much weaker.

We numerically model the system based for a z-cut PPLN microresonator with a 1-THz free spectral range and a cavity linewidth of 15 MHz at all resonances. We choose probe and detuning parameters to maximize Eqn. (4), which corresponds to $\rho = 100$ MHz, $\delta = 33$ MHz, and a probe power of 61 pW. The input photon profile and temporal response of the measurement is shown in Fig 1(e). We compare the strength of signal versus shot noise for various integration times, which are shown in Fig 1(f). We observe that a signal-to-noise ratio (SNR) of 1 can be achieved with the suitable parameters. Further improvement of SNR can be achieved by improving the Q. Alternatively, we can apply quantum metrology techniques on the probe beam, such as using squeezed states, to boost the SNR.

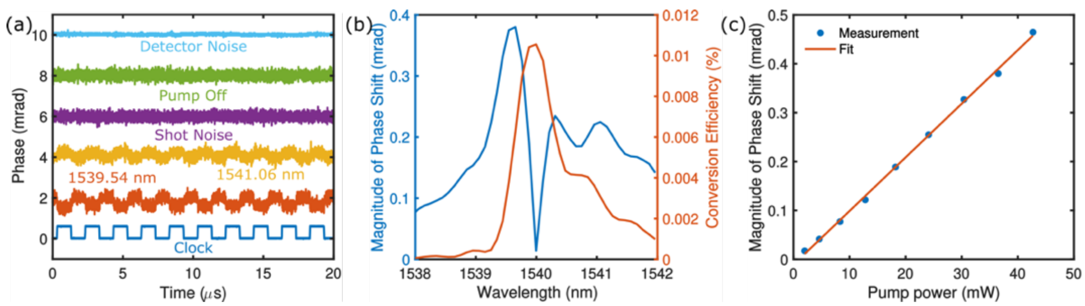

Fig. 2. (a) Temporal measurement of induced phase shift by a modulated pump laser. (b) Amount of induced phase shift versus pump wavelength and the corresponding SFG efficiency. (c) Amount of induced phase shift versus pump power.

As a proof-of-principle demonstration, we use a bulk 4-cm-long PPLN crystal as our nonlinear medium and perform the experiment using a shot-noise-limited free-space interferometer. The laser for probe and local oscillator (LO) is chosen to be 1563 nm with a split power of 1 mW and 12.4 mW, respectively. We focus the beam in the crystal such that its beam waist and Rayleigh range are 37 μm and 6.1 mm, respectively. Due to a lack of waveguide confinement and cavity enhancement, the strength of XPM in the PPLN crystal is many orders of magnitude weaker than that in the proposed PPLN microresonator. However, we can use this system to characterize the effective n_2 coefficient which is independent of mode volume and cavity Q. We use 36 mW (peak power) of square-wave pump [green beam in Fig. 1(a)] to impart phase shift on the probe beam and perform a balanced measurement. Figure 2(a) shows the temporal change of probe phase when the pump is modulated by the clock signal. The shot-noise level is measured by blocking the pump and probe beams, and the interferometer noise level is measured by only blocking the pump beam. The excellent agreement of the two noise measurements indicates that the interferometer is shot-noise limited. As we change the pump wavelength, we observe both positive (1541.06 nm) and negative (1539.54 nm) phase shifts, which is due to the sign of phase mismatch. We measure a maximum phase shift of -0.38 mrad, which is equivalent to that induced by a $\chi^{(3)}$ medium with $n_2 = -6\times10^{-12}$ cm^2/W. This value is 600× larger than the intrinsic n_2 of 1×10^{-15} cm^2/W. We verify that the magnitude of the phase shift is a function of phase mismatch by sweeping the pump wavelength [Fig. 1(b)]. The asymmetry between the positive and negative phase shifts is due to the wide spread of k-vectors in the focusing region, which results in complicated phase mismatching profiles. We further verify that the amount of phase shift scales linearly against pump power, which is the case before the saturation power is reached.

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