Photonic Interference Beyond Two Modes

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Abstract: We propose multipartite Bragg-scattering to perform all-to-all transformation among *N* frequency modes, realizing a bosonic *N*-level system. We demonstrate the *N* = 3 case illustrating a pathway towards scalability for frequency-domain optical quantum information systems.

Solving complex problems in quantum information science has been challenging due to noise and size limitations [1]. In order to advance beyond the NISQ era (noisy, intermediate-scale) towards fault-tolerant circuits, all quantum information platforms must scale to larger sizes without increasing error rates. Scalability is particularly crucial for optical quantum computing proposals that circumvent low optical nonlinearities by increasing the complexity of input states as well as the number of information channels [2-4]. At the heart of such schemes is the ability to interfere optical modes on a beamsplitter. However, scaling spatial or polarization beamsplitters incurs losses and is technically challenging, adding to the resource overhead required for optical quantum information.

A promising alternative to manipulating the spatial modes of the light fields is through the use of the frequency domain. Utilizing the nonlinear optical process of Bragg scattering four-wave mixing (BS-FWM), it is possible to realize a beamsplitter transformation between two frequency modes in both the classical and quantum regimes [5-7]. As in classical telecommunications, the frequency domain benefits from scalability via efficient wavelength-division multiplexing. Despite this promise, two-photon interference between more than two frequency modes has not yet been demonstrated, although $N \times N$ transformations for $N > 2$ have been shown for classical inputs [8,9] as well as for single or parallel qudits using the electro-optic approach (e.g. [10,11]). While conventional BS-FWM relies on two strong classical pump fields to couple two frequency modes, multipartite Bragg-scattering employs additional pumps to allow simultaneous all-to-all coupling between N frequency modes, comprising a bosonic N-level system [12].

Here we study multipartite Bragg-scattering with three pumps on a set of three frequency modes, i.e. a bosonic three-level system with interaction between all levels. The induced 3×3 unitary transformation [13] can be tuned by varying the pump power, which in the case of two pumps corresponds to adjusting the transmission coefficients of a beamsplitter. We investigate the quantum behavior in which two photons are injected into different ports of the system and compare it to the case of injecting two coherent-state fields.

We develop a theoretical model for the single-count and coincidence rates at the output of the 3-port frequency beamsplitter for the cases of attenuated coherent state and photon-pair inputs. The annihilation operators for each of the three interacting frequency modes (or 'levels') are represented by a_0, a_1, and a_2, which in the experiment correspond to the wavelengths 1280, 1283, and 1285 nm, respectively). Both input states are at two wavelengths corresponding to modes 0 and 2. In the ideal case of equal pump powers P and perfect phasematching, the effective interaction Hamiltonian (in the frame of the pulse) is given by the sum of three beamsplitter-type transformations, one for each pair of levels, such that,

$$H_{eff} = 2\gamma P\left(a_0^\dagger a_1 + a_1^\dagger a_2 + a_2^\dagger a_0 + h.c.\right),$$

where γ is the nonlinearity (proportional to the third-order susceptibility $\chi^{(3)}$). The observed singles rates for the i^{th} field are then proportional to $\langle a_i^\dagger a_i \rangle$, and the coincidence rates are given by the second-order correlation function $\langle a_i^\dagger a_j^\dagger a_j a_i \rangle$. We observe that, in contrast to the singles rates, second-order correlation functions can differentiate statistics between the two-mode weak coherent state and photon-pair inputs.

In our experiment, the weak coherent input state is prepared by strongly attenuating two O-band lasers at 1280 and 1285 nm to the single-photon level. To generate photon pairs, we use spontaneous four-wave mixing (SFWM) in a silicon-nitride ring microresonator (200-GHz free spectral range) and collect photons from two resonances equidistant from the SFWM pump at the two weak coherent-state frequencies. Since the SFWM pump coincides with frequency mode 1, we strongly filter it through a chain of fiber Bragg gratings to a level approximately 20 dB below the photon-pair intensity to avoid contaminating the input state. Once the two-mode input is prepared, it is multiplexed together with three strong pulsed C-band BS-FWM pumps before entering the nonlinear Bragg fiber. After propagating 100 m in the fiber, the transformed O-band fields are separated via three free-space filters before entering individual superconducting nanowire single-photon detectors (SNSPDs), which is equivalent to reading out the population of each of the three levels. Detection events are then recorded with our time-tagging module as the power of the BS-FWM pumps (hence the interaction strength) is scanned through the full range available experimentally.

A subset of the resulting measured normalized singles and coincidence rates are plotted below. Fig. 1a displays the singles rates for the weak coherent states and is in excellent agreement with theoretical analysis. In the case of a photon-pair input (Fig. 1b), we plot normalized coincidence rates between modes a_0 and a_2, obtained from integrating the measured delay histogram over the inverse microresonator linewidth. When compared with the same observable for the coherent state in Fig. 1b, it is evident that the second-order correlation function uniquely reveals the fundamentally nonclassical nature of the input state. To accurately describe the full behavior of the system, we incorporate multiphoton emission from the microresonator in addition to asymmetric losses in the photon paths. We estimate the multiphoton parameter via a separate heralded Hanbury Brown-Twiss measurement, and the relative losses are based on measurements concurrent with the experiment. Such losses would not appear in our coincidence measurements in the absence of multiphoton emission. Thus, both are required to account for the measurements of Fig. 1b. This is the first time, to the best of our knowledge, such interference between two correlated photons among > 2 modes has been observed in the frequency domain. The general $N \times N$ unitary transformation merely requires $O(N^2)$ pumps, which would allow arbitrary control over each coupling in the system.

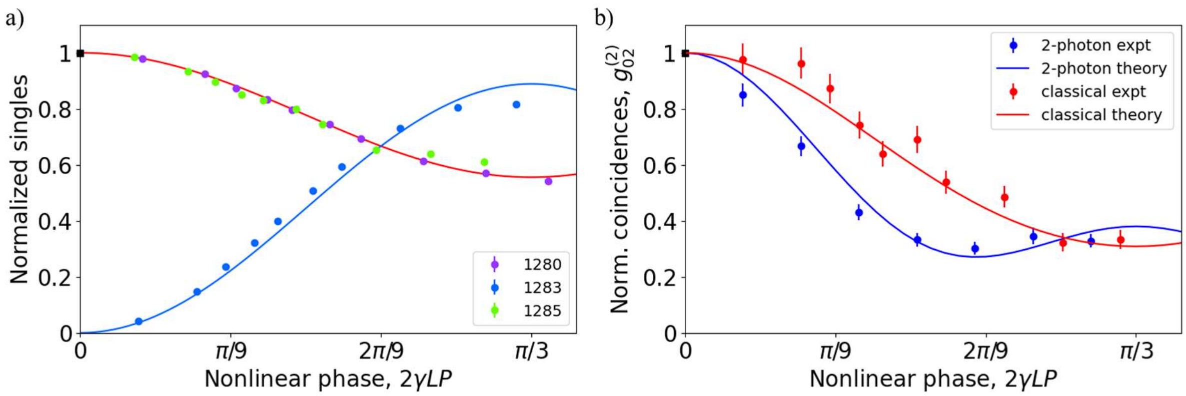

Figure 1. a) Singles rates for the two-mode weak coherent-state input. Theory curves are shown in solid lines. Error bars are smaller than the data marker, computed assuming Poisson statistics. b) Comparison between coherent state versus photon pair coincidence rates between modes a_0 and a_2. In both figures, the point at zero nonlinear phase represents the normalization rate, and L is the interaction length.

Our experiment demonstrates the possibility of achieving simultaneous all-to-all coupling between an arbitrary number of modes in the quantum regime. Through use of an optical frequency comb source for the multi-pump source, our system has the potential to enhance the scalability of all optical quantum information processing protocols that rely on beamsplitter transformations, including boson sampling [12] and cluster state generation [14]. Our results show promise for the scalability of $N \times N$ photonic quantum information platforms.

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