A programmable electro-optic Bell-state analyzer for spectrally distinguishable photons

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Abstract: We demonstrate a Bell-state analyzer that operates directly on frequency mismatch and unambiguously distinguishes two of four Bell states with accuracy exceeding 98%, opening a feasible path to wavelength-multiplexed quantum networks.

Unlocking the full potential of quantum technology will require not just progress in developing standalone systems, but also in mediating communication and entanglement between these systems across a network [1]. Unlike classical counterparts, quantum networks cannot rely on amplification to transmit quantum information over long distances and instead depend on heralded entanglement generation protocols, which are usually based on Bell state measurements [2]. However, the quality of generated entanglement depends on spectral indistinguishability of photons participating in the joint measurement. Here, we demonstrate a Bell state analyzer (BSA) that accommodates wavelength mismatch by using interleaved frequency beam splitters and report unambiguous detection of two frequency-bin Bell states with discrimination accuracy in exceeding 98%. Our frequency beam splitters are synthesized using a quantum frequency processor (QFP) [3], which permits reconfiguration with simple electronic control and supports parallel quantum operations across many spectral channels. The realization of a BSA in a parallelizable and programmable platform has the potential to support quantum networks that rely on heterogeneous nodes and spectral multiplexing.

In a BSA, two photons, each entangled with separate qubits (matter-based or photonic), are mixed at a 50 : 50 (spatial) beamsplitter. A subset of the possible detection outcomes, usually signified by two coincident detector clicks, heralds projection of the undetected qubits onto a *known* entangled state. This is a probabilistic process as only two of four Bell states can be discriminated unambiguously using only linear optics [4]. If the two photons are spectrally distinguishable, the undetected qubits are not projected onto a Bell state and will instead have an additional phase factor. Time-resolved measurements with fast detectors, in combination with temporal postselection or feedforward, can overcome this is overcome this limitation, but it comes at the cost of the entanglement rate [5] or system complexity [6], respectively. Even then fidelities are lower than what one would obtain with spectrally indistinguishable photons. To lift this trade off, we synthesize a BSA where two frequency-bin entangled photons are mixed not with a spatial beamsplitter, but rather with frequency beamsplitters [3], which intentionally leverage frequency mismatch.

Figure 1(a) (*right*) is a high-level illustration of our BSA for frequency-encoded photonic qubits. The operation is analogous to the BSA for polarization qubits [7] [see Fig. 1(a) (*left*)], where corresponding modes (H with H and V with V) are mixed at a 50 : 50 spatial beamsplitter. This is followed by demultiplexing of all the distinct modes that can be populated – two polarization states in each of two possible paths. The equivalent operations in the frequency domain are two parallel (and interleaved) Hadamard transformations followed by spectrally-resolved coincidence measurements. As with the spatial analog, only the $|\Psi^+\rangle$ and $|\Psi^-\rangle$ Bell states can be identified without ambiguity, and we validate this functionality by demonstrating that each of these states gives rise to a unique coincidence pattern.

Figure 1(b) shows our experimental setup. Time-frequency–entangled photons are generated by pumping a periodically poled lithium niobate ridge waveguide (PPLN) with a continuous-wave laser at 780 nm. We use an etalon (not shown) and pulse shaper (BFC shaper) to carve four energy-correlated frequency modes $\{A_0, A_1, B_0, B_1\}$, which

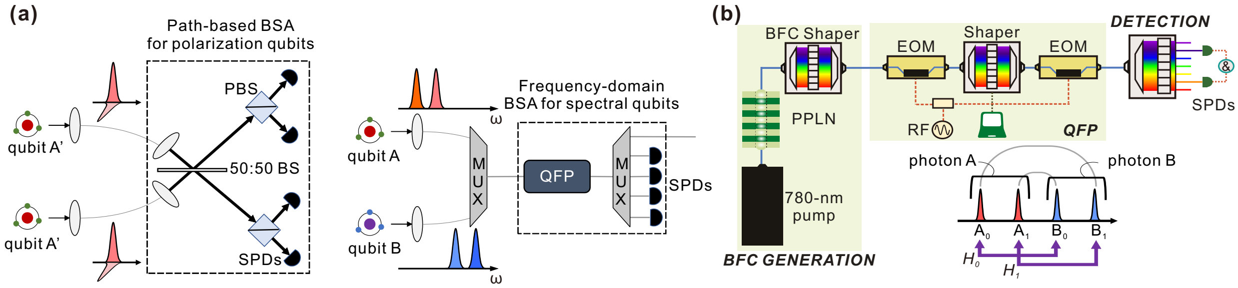

Fig. 1. (a) Bell state analyzers based on spatial (*left*) and frequency (*right*) beam splitters. (b) Experimental setup and concept illustration of interleaved Hadamard transformations (*inset*).

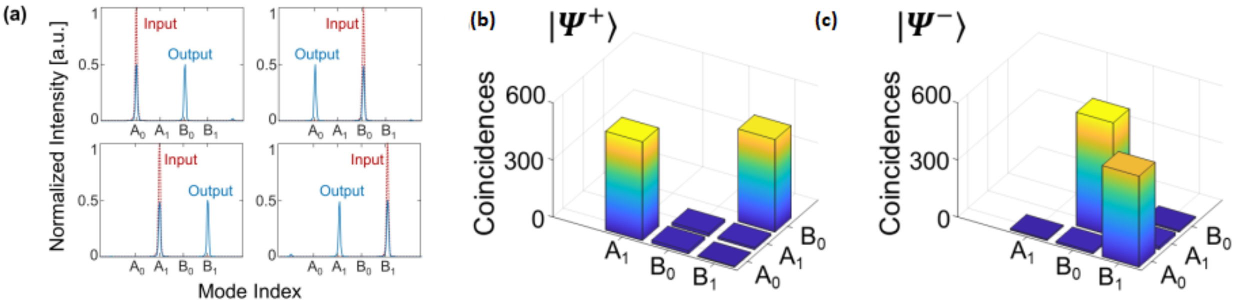

Fig. 2. (a) Experimentally measured output spectra for single-frequency input at mode $\{A_0, A_1, B_0, B_1\}$. (b-c) Coincidence counts registered after $|\Psi^+\rangle$ (b) and $|\Psi^-\rangle$ (c) pass through the BSA.

projects the biphoton onto state $|\Psi^\pm\rangle \propto |1_{A_0}\rangle|1_{B_1}\rangle \pm |1_{A_1}\rangle|1_{B_0}\rangle$ [choice of + or − state determined by phase applied to $|1_{A_0}\rangle|1_{B_1}\rangle$ by BFC shaper]. The center-to-center separation between signal and idler is 40 GHz while the two modes in each photon are 20 GHz apart with an intensity full-width at half-maximum of 1 GHz. Parallel and interleaved Hadamard transformations [frequency beamsplitters; see Fig. 2(a) for mode transformation spectra] are implemented with a QFP, whose output is frequency demultiplexed using another pulse shaper such that different frequency modes are routed to the two detectors (SPDs). Coincidence counts for all 12 detector combinations (excluding A_0A_0, A_1A_1, B_0B_0 and B_1B_1) are integrated over a 1.5 ns window for a total of 120 seconds.

Experimental results are presented in Figure 2. For the $|\Psi^+\rangle$ state [Fig. 2(b)], coincidences register between the two frequencies corresponding to the original idler modes (A_0A_1) or the two original signal modes (B_0B_1), as expected from theory [7]. On the other hand, the $|\Psi^-\rangle$ state [Fig. 2(c)] results in coincidences between one of the original idler modes with one of the original signal modes (A_0B_1 or A_1B_0), thereby allowing one to unambiguously distinguish $|\Psi^+\rangle$ from $|\Psi^-\rangle$. We then calculate the discrimination accuracy N_c/N_T, where N_c and N_T correspond to the sum of correct measurement results and the sum of all events identifiable as $|\Psi^+\rangle$ or $|\Psi^-\rangle$, respectively. For these two Bell states, we achieve accuracies of 98.6% and 98.1% for $|\Psi^+\rangle$ and $|\Psi^-\rangle$, respectively, reported without accidental subtraction.

While the specific BSA realized here operated on frequency-bin entangled photons, the concept is easily extended to spectrally distinguishable photons encoded in other degrees of freedom (DoFs). Our focus on frequency encoding is motivated by the many advantages of this DoF. Frequency (energy) is the most common encoding variable for matter-based qubits, as well as offers natural stability in optical fiber, straightforward measurement with high-efficiency filters and detectors, and compatibility with wavelength-division multiplexing. From the standpoint of performance, we have previously shown that a three-element QFP can implement near-deterministic frequency beamsplitters with gate fidelities exceeding 0.999999 [8]. Furthermore, this paradigm permits massive parallelization of quantum operations [3] in a single device without any crosstalk and, most importantly, within a single fiber-optic spatial mode, thereby enabling natural phase stability. A crucial enabler of this technology will be the migration of QFP functionality to an integrated photonic platform. This offers two key advantages – a significant reduction in optical loss and access to narrow linewidth filters [9] to permit operations on modes separated by a few GHz or less, a scale compatible with photonic frequency qubits from matter-based quantum systems.

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