Frequency-bin Bell state generation via successive single and dual spectral-line pumping

Suparna Seshadri,[1] Hsuan-Hao Lu,[1] Daniel E. Leaird,[1] Andrew M. Weiner,[1] and Joseph M. Lukens[2,*]

[1] *School of Electrical and Computer Engineering and Purdue Quantum Science and Engineering Institute, Purdue University, West Lafayette, Indiana 47907, USA*

[2] *Quantum Information Science Section, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

**lukensjm@ornl.gov*

Abstract: We demonstrate a simple and versatile scheme to generate all four two-dimensional frequency-bin Bell states using single and dual spectral-line pumps and passive filtering. Experimentally, we measure ≥97% fidelity for all states.

Bell states are ubiquitous in both the fundamental study of quantum entanglement and the practical goals of quantum information processing. A variety of archetypal quantum communication protocols such as dense coding [1], teleportation [2], and entanglement swapping [3] crucially rely on Bell states and their measurement. The two-dimensional Bell basis comprises four maximally entangled states typically written as $|\Psi^{\pm}\rangle \propto |01\rangle \pm |10\rangle$ and $|\Phi^{\pm}\rangle \propto |00\rangle \pm |11\rangle$. Polarization-entangled Bell states were the first to be demonstrated and have been utilized heavily in quantum information experiments. Bell states have also been successfully demonstrated in time bin [4], orbital angular momentum [5], and path [6] encodings. Frequency-bin encoding has emerged as a promising platform for quantum information processing due to its compatibility with both on-chip integration and transmission over optical fiber networks. In the frequency degree of freedom, the generation of *negatively* frequency-correlated $|\Psi^{\pm}\rangle$ states (under the convention where the logical $|1\rangle$ has higher frequency than logical $|0\rangle$) can be trivially accomplished as dictated by energy conservation in a continuous-wave (CW) driven nonlinear parametric process. However, the generation of *positively* frequency-correlated $|\Phi^{\pm}\rangle$ states is inherently more challenging. Using a quantum frequency processor, the $|\Psi^{\pm}\rangle$ Bell states can be deterministically transformed to $|\Phi^{\pm}\rangle$ states by applying parallel Hadamard and phase gates [7]. But, such transformations require multiple active elements after photon generation, increasing complexity and incurring extra insertion losses. In this work, we demonstrate a much simpler scheme for generating all frequency-bin Bell states in a single setup by successively driving the spontaneous parametric down-conversion process (SPDC) with single and dual spectral-line pumps, and applying a single programmable spectral filter to postselect the desired Bell state from the broadband biphoton spectrum.

Figure 1(a) provides a schematic of the experimental setup. A CW laser centered at ∼780.3 nm ($\omega_{p,0} = 2\pi \times 384.2$ THz) is launched into an electro-optic intensity modulator (EOIM) driven by a 25 GHz radio-frequency (RF) sinusoidal waveform. The output from the EOIM pumps a fiber-pigtailed periodically poled lithium niobate (PPLN) waveguide engineered for type-0 phase matching. We use pulse shaper 1 to carve two 14 GHz-wide frequency bins separated by 25 GHz on both sides of the CW laser's half-frequency ($\omega_{p,0}/2$). The EOIM is set to one of the two desired modes of operation such that either single or dual pump lines are generated at the output. The conceptual illustration of the proposed scheme is shown in Figs. 1(b,c). The more conventional case of a single-line pump realizes the $|\Psi^{\pm}\rangle$ states, while the dual-line case of frequency-shifted, coherent SPDC processes engineers a total quantum state $|\Phi^{\pm}\rangle$ with positive frequency correlations after postselection by spectral filtering.

In the first experiment, high attenuation is applied on the 25 GHz RF waveform modulating the EOIM to enforce a single carrier ($\omega_{p,0}$) at its output. Two frequency-bins separated by 25 GHz are carved from each of the signal and idler spectra ($\{S_0, I_1\}$ and $\{S_1, I_0\}$ at offsets of ±152.5 GHz and ±177.5 GHz from the pump's half-frequency). The resulting state is of the form $|\Psi_{IS}\rangle = |I_0, S_1\rangle + e^{i\alpha}|I_1, S_0\rangle$, where the phase α is dependent on the difference in delays traversed by the biphotons. We expect $\alpha = 0$ since both photons traverse identical links with negligible dispersion. We verify the same in the experiment by measuring the coincidences between all pairs of signal and

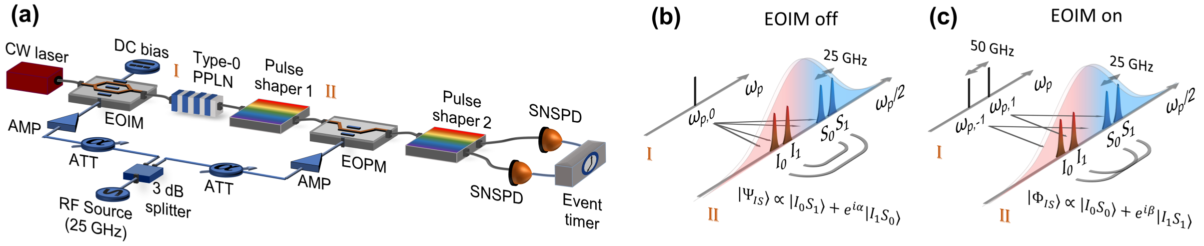

Fig. 1. (a) Experimental setup. Illustration of the working scheme for the generation of (b) $|\Psi\rangle$ and (c) $|\Phi\rangle$ states, when EOIM is turned off and on, respectively. AMP: RF amplifier, ATT: variable RF attenuator, SNSPD: superconducting nanowire single-photon detector.

This manuscript has been co-authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

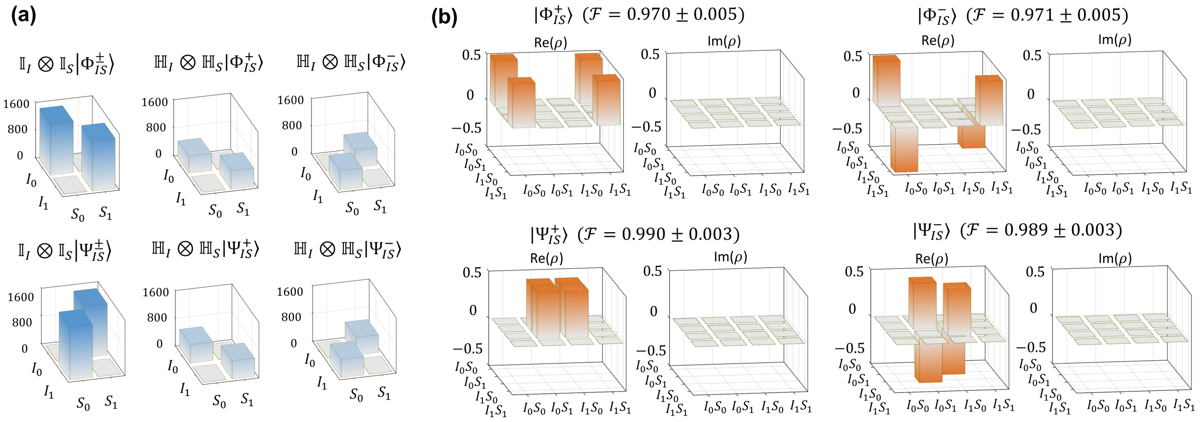

Fig. 2. (a) Coincidences between signal and idler frequency bins measured after successively applying the gate operations $\mathbb{I}_I \otimes \mathbb{I}_S$ and $\mathbb{H}_I \otimes \mathbb{H}_S$. (b) Real and imaginary parts of the Bayesian-mean-estimated density matrices of all four Bell states, computed from the measurements in (a).

idler frequency bins as the spectral phase on the bin pair $|I_1 S_0\rangle$ imparted by pulse shaper 1 is scanned and a probabilistic Hadamard gate [8] is applied on both the photons using an electro-optic phase modulator (EOPM). Finally, the phase α is set to 0 (π) using pulse shaper 1 to obtain $|\Psi^{+}_{IS}\rangle$ ($|\Psi^{-}_{IS}\rangle$).

In the second experiment aimed at generation of $|\Phi^{\pm}\rangle$ states, the EOIM is operated for carrier-suppressed modulation (with DC bias set to its half-wave voltage). This results in first-order sidebands (at $\omega_{p,-1}$ and $\omega_{p,1}$) spaced by 50 GHz. The following SPDC process generates time-energy entangled biphotons in coherent superpositions of broadband spectral amplitudes centered at half of the pump-sideband frequencies. The frequency-bins $\{I_0, I_1, S_0, S_1\}$ are carved at the same center frequencies as described earlier, resulting in a two-qubit entangled state ideally of the form $|\Phi_{IS}\rangle = |I_0, S_0\rangle + e^{i\beta}\,|I_1, S_1\rangle$. Although the pump line at $\omega_{p,1}$ ($\omega_{p,-1}$) can also generate an idler (signal) photon in frequency bin I_0 (S_1), its energy-matched signal (idler) does not lie within the computational space, and hence such contributions do not exist in the postselected $|\Phi_{IS}\rangle$ state in the coincidence basis. The phase β is a fixed common-mode phase accumulated by the biphotons due to the RF modulation phase and mean optical delay traversed by the biphotons. We determine the phase β in the same fashion as with α; the measured value is compensated for and set to 0 (π) using pulse shaper 1 to obtain $|\Phi^{+}_{IS}\rangle$ ($|\Phi^{-}_{IS}\rangle$).

The coincidence counts between each pair of signal and idler frequency bins of the prepared $|\Psi^{\pm}_{IS}\rangle$ and $|\Phi^{\pm}_{IS}\rangle$ Bell states is measured in two mutually unbiased basis, $Z \otimes Z$ and $X \otimes X$ (via gate operations $\mathbb{I}_I \otimes \mathbb{I}_S$ and $\mathbb{H}_I \otimes \mathbb{H}_S$, respectively). The resulting joint spectral intensities (JSIs) are plotted in Fig. 2(a). Consistent with theory, we find: (i) the $Z \otimes Z$-basis measurement indicates *positive* and *negative* frequency-correlations in the $|\Phi^{\pm}_{IS}\rangle$ and $|\Psi^{\pm}_{IS}\rangle$ states, respectively, and (ii) transitioning from identity to Hadamard operations for the $X \otimes X$-basis measurement produces frequency correlations that vary depending on the phase of the respective Bell state ($\pm$). Bayesian mean estimation [9] allows us to infer the full density matrix of each state from the measured JSIs in the $Z \otimes Z$ and $X \otimes X$ bases. The estimated density matrices shown in Fig. 2(b) have fidelities $\geq 97\%$. Moving forward, it will be interesting to explore the extent to which this technique can be generalized to higher-dimensional entanglement, the impact of coincidence basis postselection on protocols using these resources states, and methods to discriminate between them using frequency-bin Bell state analyzers [10].

We thank AdvR for loaning the PPLN ridge waveguide. A portion of this work was performed at Oak Ridge National Laboratory, operated by UT-Battelle for the U.S. Department of Energy under contract no. DE-AC05-00OR22725. Funding was provided by the National Science Foundation (1839191-ECCS, 2034019-ECCS) and U.S. Department of Energy (Early Career Research Program).

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