Scaling Entanglement in the Optical Frequency Comb

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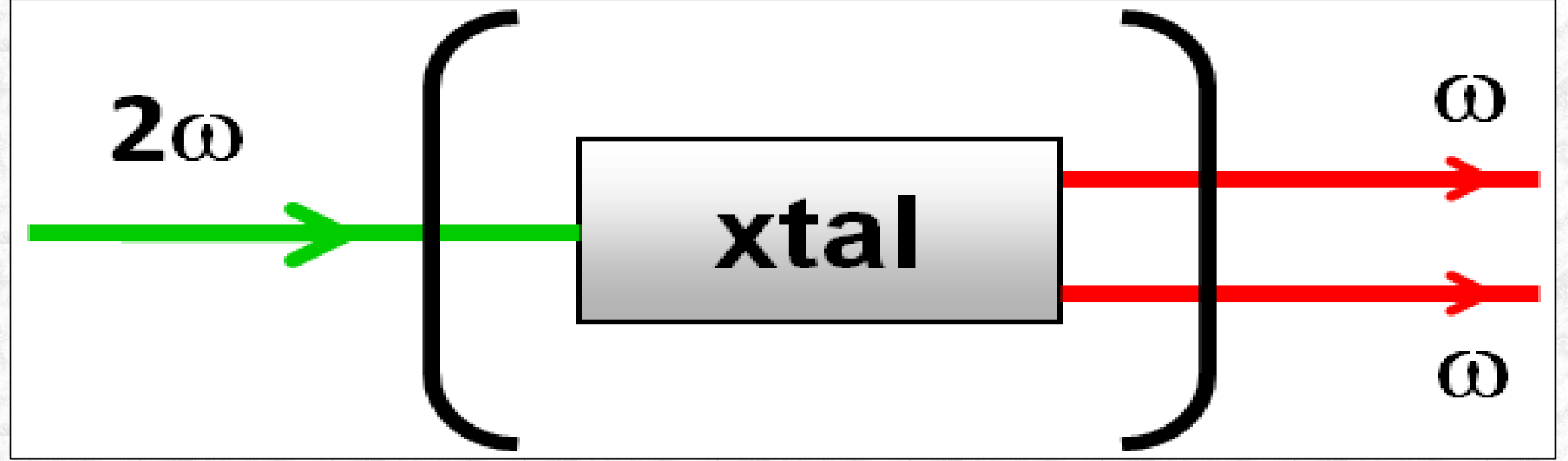
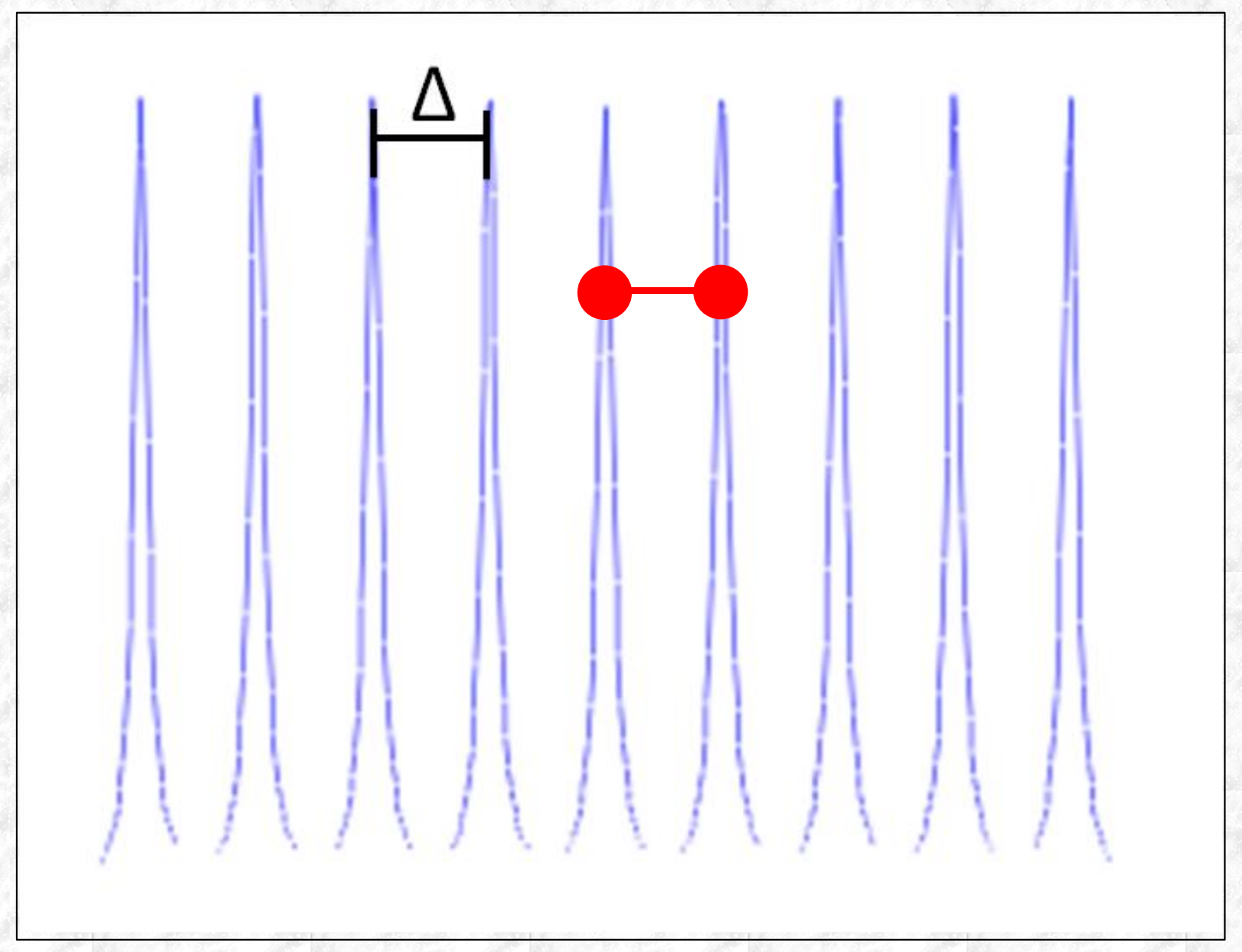
BACKGROUND

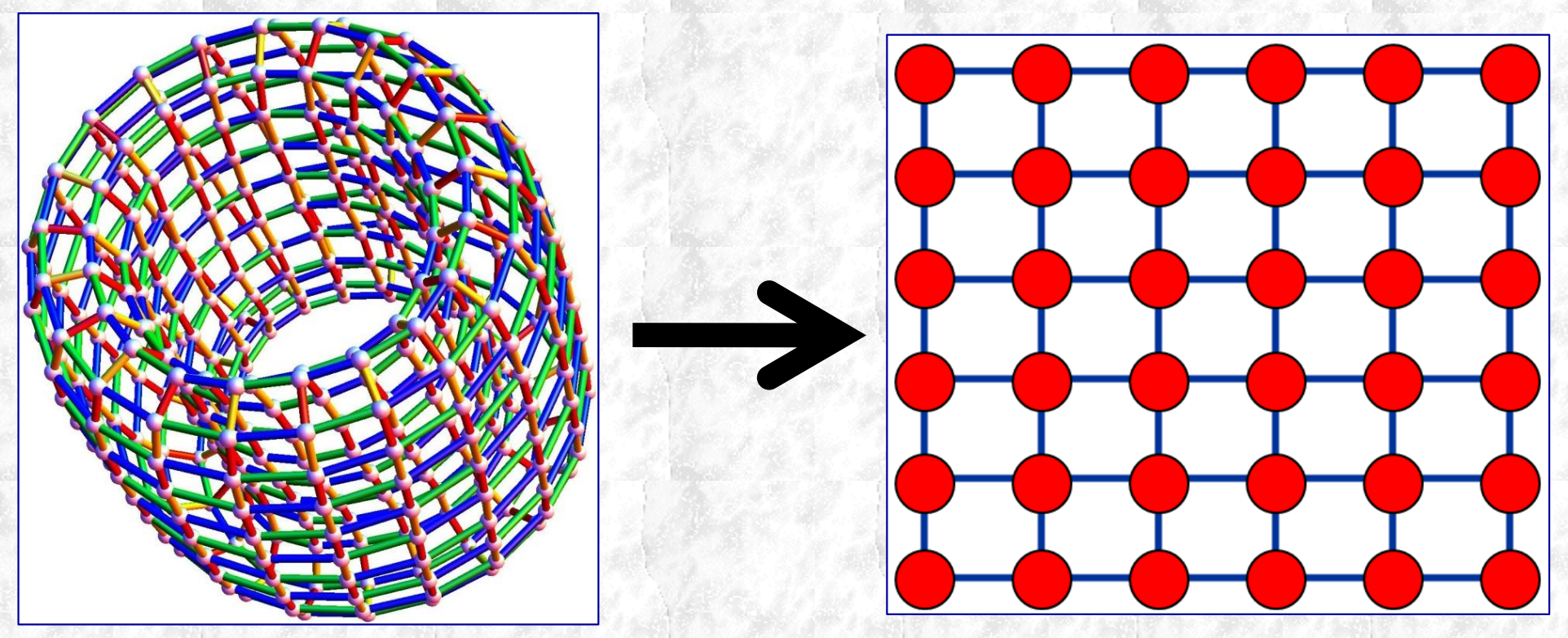
A quantum computing protocol known as one-way quantum computing requires the creation of a large square-grid entangled state known as a cluster state. Calculations can then be made by making projective measurements on the individual components of the entangled state. Such measurements alter the remaining portion of the cluster but leave it entangled. We and our collaborators have shown that it is theoretically possible to create such an entangled state by linking the equally spaced resonant frequency modes of an optical cavity[2].



In an optical parametric oscillator (OPO), photons from a pump beam are annihilated to create correlated photon pairs.



The resonant frequency modes emitted from a cavity form a comb with teeth equally spaced by the cavity's free spectral range, Δ. These modes can be populated by correlated photon pairs, thereby entangling the modes.



The toroidal cluster on the left, which can be generated in a single optical cavity, can be unwrapped to create a square grid cluster state suitable for quantum computing.

OVERVIEW

Driven by the promise of exponential speedup for quantum simulation and code breaking, the development of a quantum computer has emerged as one of the most exciting challenges to the physics and engineering community. A major hurdle to the experimental realization of a quantum computer is the scaling of nonlocal correlations between quantum bits, a.k.a. entanglement. Researchers have worked tirelessly to create large entangled systems "bottom-up," by linking individual quantum systems one by one, which has proven extremely difficult. Here, we successfully demonstrate a "top-down" approach based on the frequency comb formed by an optical cavity. We experimentally link a record 60 quantum modes into 15 sets of quadripartite entangled cluster states[1]. This result paves the way for the realization of large-scale entangled states for universal quantum computing.

EXPERIMENTAL METHODS

As a step towards making one large cluster state, it is possible to use the scalability afforded by the optical frequency comb to create many smaller clusters[3]. This requires the insertion into our cavity of a nonlinear crystal capable of linking Y-polarized modes with Z-polarized modes, as well as Z-polarized modes with other Z-polarized modes. Our cavity is adjusted so that each comb frequency is comprised of both Y- and Z-polarized light. The light emitted from our cavity consists of numerous four-mode entangled cluster states, which are generated simultaneously. These states can be individually probed by interfering the modes output by the cavity with higher powered local oscillator beams created by an electro-optical modulator at frequencies of $\omega_L \pm \Omega$.

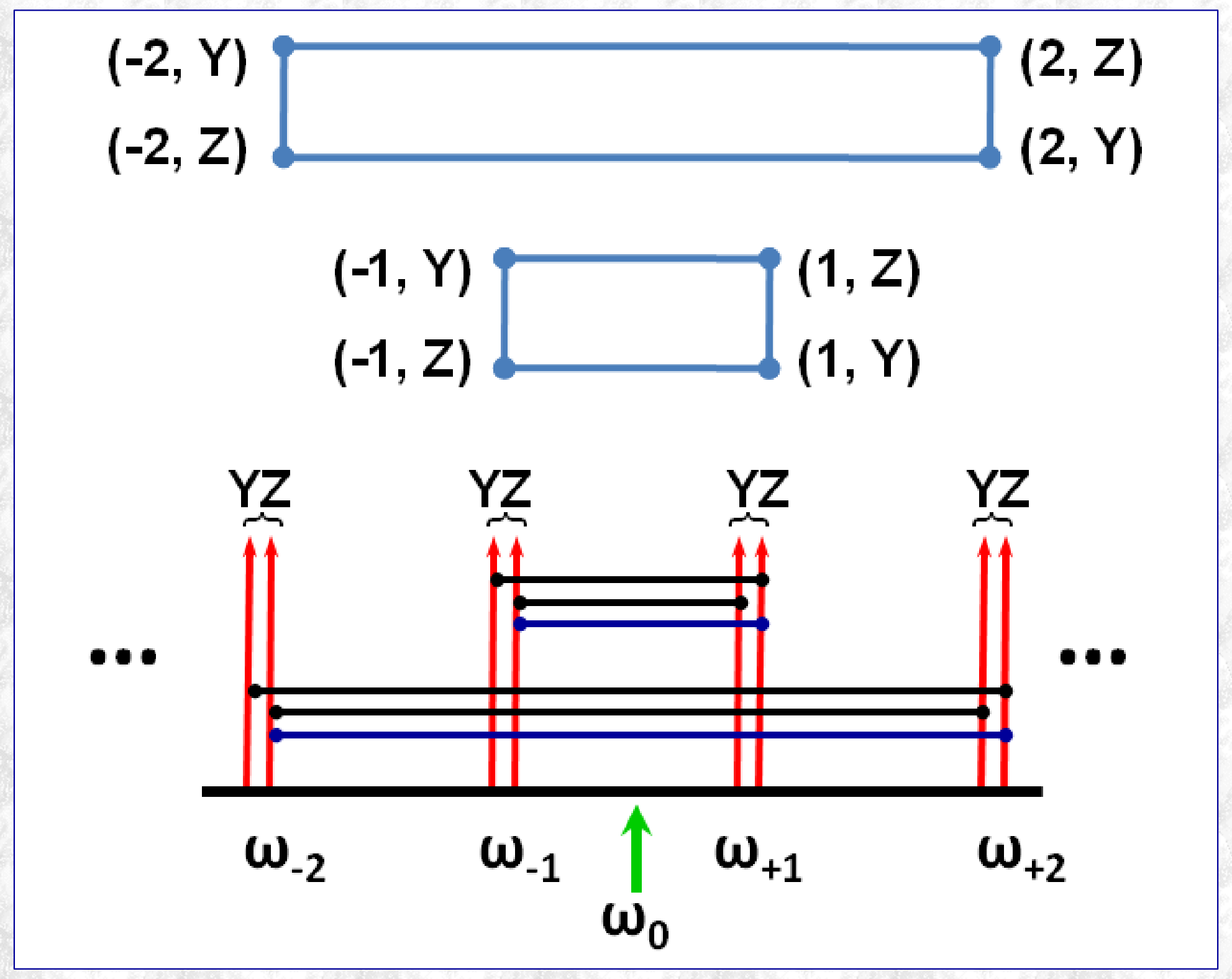
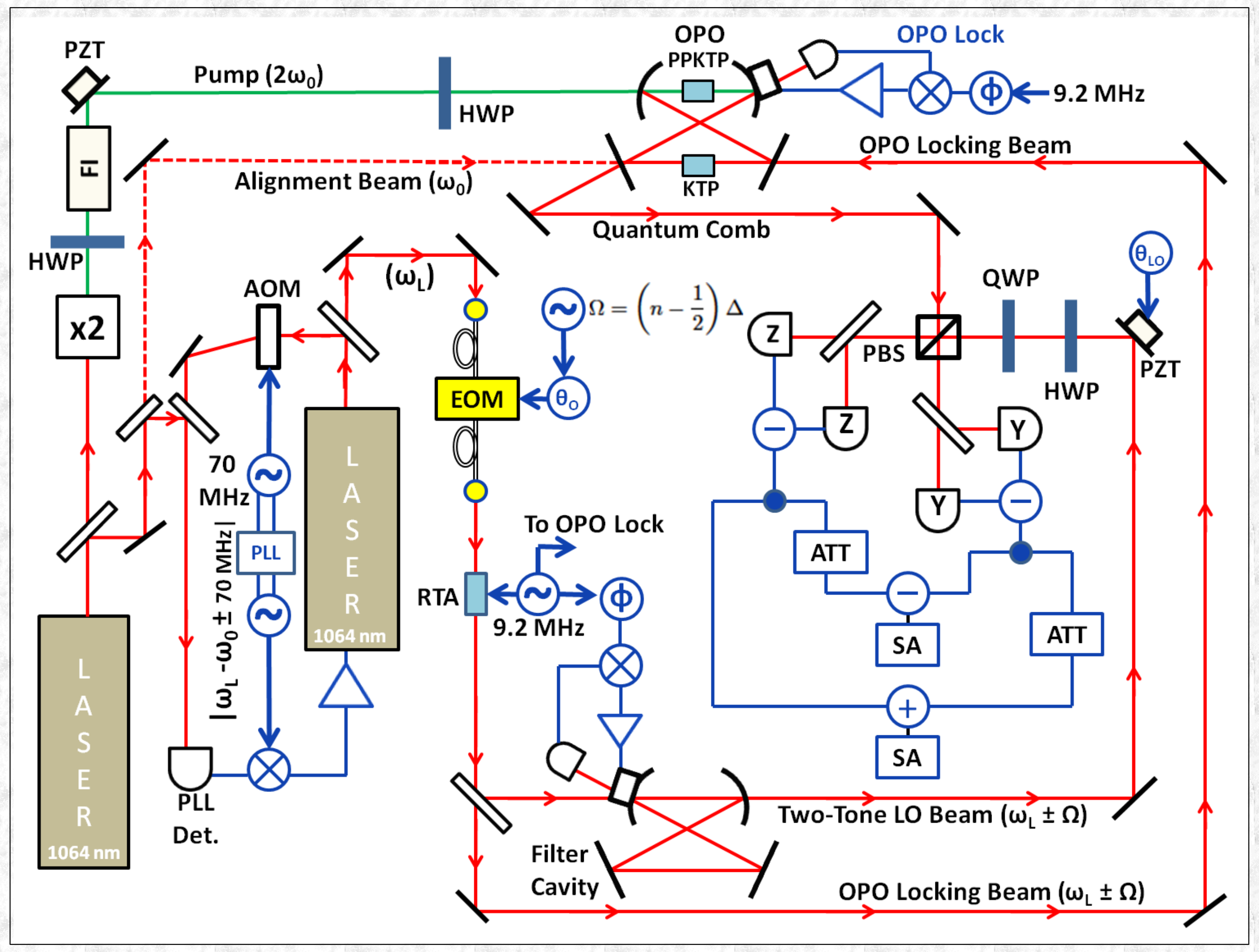


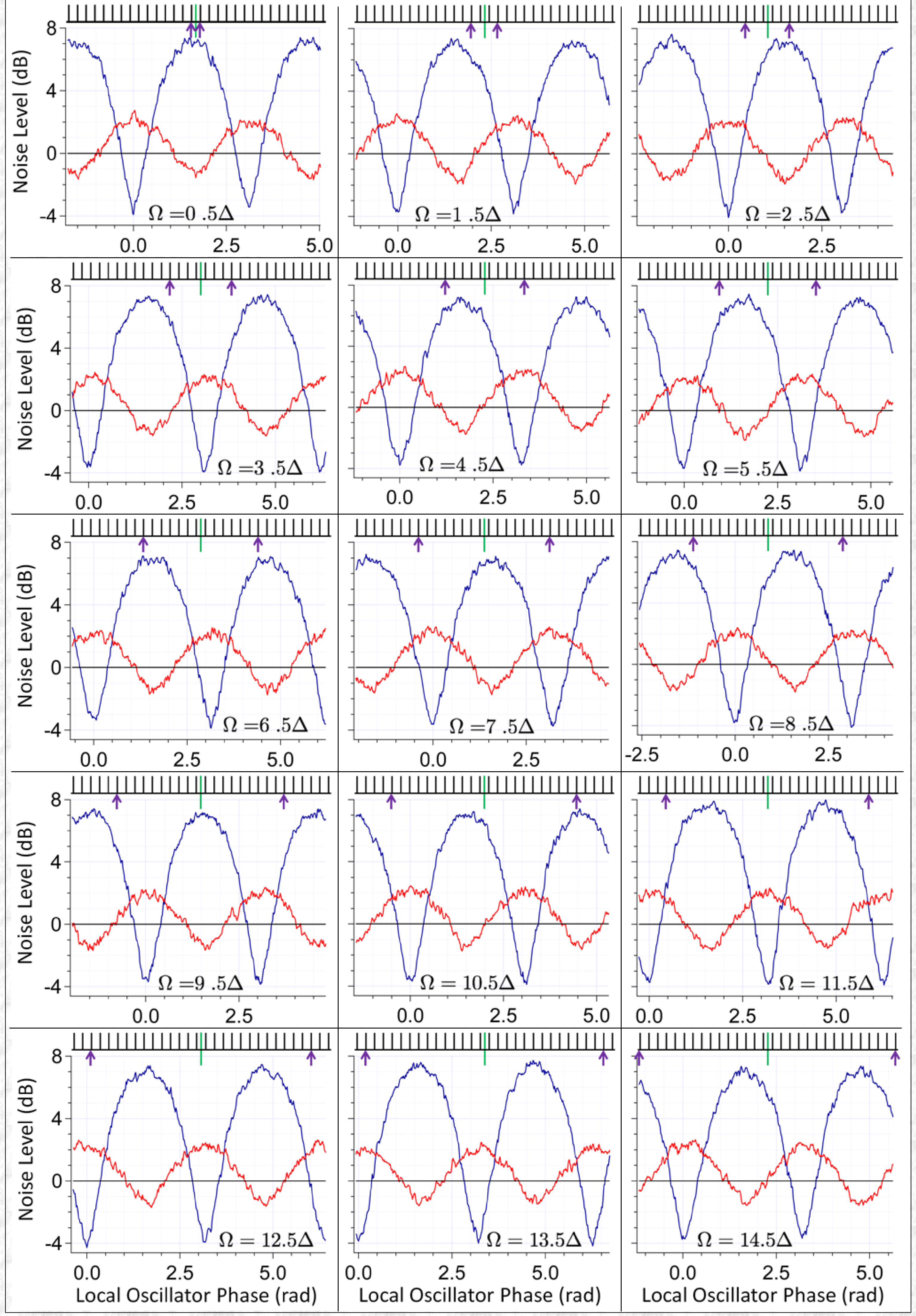
Diagram displaying the experimental links that lead to cluster state formation.



Experimental setup.

The chart on the right shows data taken at fifteen different sideband frequencies, with each graph representing a different cluster state. The red and blue traces represent measurements of the two quadripartite correlations necessary to ensure entanglement. Traces falling below the black line are exhibiting a reduction in their quantum noise level, and are referred to as squeezed. In these measurements, squeezing of both traces indicates entanglement. As you can see from the data, the squeezing level is constant across the optical frequency comb. The number of measured clusters was limited only by the local oscillator frequencies obtainable with our current equipment. We predict the actual number of cluster states created to be on the order of 50 or more. We also made measurements showing that correlations between modes in different cluster states never display squeezing.

RESULTS



Experimental data displaying equal-strength entanglement signals over 60 cavity modes, thereby showing the potential of the optical frequency comb for scaling entanglement.

REFERENCES

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3. H. Zaidi, N.C. Menicucci, S.T. Flammia, R. Bloomer, M. Pysher, and O. Pfister, "Entangling the optical frequency comb: simultaneous generation of multiple 2x2 and 2x3 continuous-variable cluster states in a single optical parametric oscillator," Laser Physics 18, 659 (2008).