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Proposal: This proposal discusses creating a modulated topological ring resonator in a photonic crystal. By modulating the ring resonator at its resonant frequencies, synthetic dimensions in frequency space can be leveraged to increase speed and efficiency while decreasing energy consumption for modern optical computing in both the classical and quantum regime.

Background: Waveguides and ring resonators have long been necessary photonic components widely used in integrated optics. Demand for smaller and smaller components has led to the gradual development of collapsing 3-D systems to nanoscale 2-D sizes. Inspired by electronic condensed matter materials, 2-D topological photonics has recently been utilized as a new way to control the propagation of light. Uni-directional photonic edge-states arise at the boundaries between two topologically-distinct photonic crystals. The properties of robustness to structural defects and uni-directional, low-loss light propagation are extremely important in quantum optics and future scalable quantum devices, inspiring inter-disciplinary research to improve these potentially superior miniature optical components.

Conventionally, physical experiments have been constrained by the number of degrees of freedom allowed by the geometric dimensionality of the system. From this, the concept of synthetic dimensions was devised as a way to circumvent the limiting 3x1 dimensions available. Synthetic dimensions are extra degrees of freedom that can be combined with spatial dimensions to create a "synthetic space" in which to do higher dimensional physics in a compact or lower-dimensional system. These synthetic dimensions can be engineered in time, frequency, polarization, orbital angular momentum states, and more. For example, using a modulator, one can place multiple states with different frequencies into a single spatial lattice unit. This can also be interpreted as a 2D lattice with frequencies of the modes as the synthetic dimension. In traditional topological insulators, transport is restricted to the spatial dimensions of the lattice. In synthetic dimensions, transport occurs on the edges of synthetic space while maintaining topologically protected transport over the bulk part of the lattice in real 3D space. My proposed system on a photonic crystal will be used to create a more compact and efficient optical component that is already widely used in optical devices.

Hypothesis: With the goal of exploiting topological edge states and compact devices, I propose to create a topological photonic ring resonator that contains synthetic dimensions in frequency space using an electro-optical modulator (EOM). By modulating the ring-resonator along its discrete resonant modes, we can propagate photons along the frequency domain and create superior optical components that can be used in scalable quantum devices of the future.

Methodology:

Task 1: Design and Simulation: First, one must modify Maxwell's equations in order to obtain a theoretical description of resonant modes of the modulator. This is because under an applied voltage, the refractive index of the photonic crystal will change. Solving the voltage-dependent additional term in Maxwell's equations will reveal the voltage required to modulate at resonant frequencies. The topological ring resonator is created by using valley photonic crystals with a triangular-loop topological edge, as shown in **Fig 1a**. The photonic crystal is a honeycomb lattice made up of rhombic unit cells with triangular air

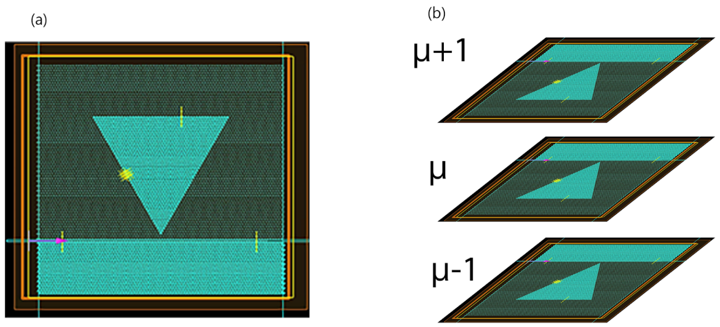

Fig. 1. (a) Schematic for ring resonator. EOM marked with multiple yellow slashes on ring resonator. (b) Different resonant modes of the topological ring resonator form a synthetic dimension.

holes etched with varying side lengths. A topological spin-Hall type waveguide is used to couple the resonant modes to the topological ring. An electro-optical modulator is used to supply voltage to the ring resonator to overlay frequencies onto photons on the ring, creating a discrete set of lattice resonant modes that will be used as a synthetic dimension shown in **Fig 1b**. The input source is a circularly polarized dipole emitter in the telecommunication band, approximately 1520 nm. Using the FDTD method in Ansys Lumerical or COMSOL multiphysics, simulations and parameter sweeps will be conducted to optimize the parameters of the topological ring resonator. These simulations will provide the spectral mode structure of the ring resonator, found when varying the voltage of the modulator and analyzing the location of intensity peaks.. The spatial electric field intensity will be analyzed in the plane of the ring resonator, with add and drop ports placed to calculate normalized transmission in different segments of the design.

Task 2: Fabrication: To experimentally verify the topological photonic ring resonator, a 170 nm thick layer of Gallium Arsenide (GaAs) will be fabricated on top of a one-micron silicon substrate. The etching is accomplished using standard electron beam lithography and dry etching techniques. When placed in the photonic crystal, quantum dots can couple/decouple the cavity and the ring resonator, allowing one to measure at which frequency modes the ring transmits light. Embedded InGaAs quantum dots will be used to probe the mode structure of the photonic ring resonator in order to modulate at the ring's resonant frequencies. Two tapered optical fibers will be placed closely on either side of the chip. The input fiber will be attached to a grating coupler used to couple incident light from the fiber to the photonic crystal waveguide. Another grating coupler is used to couple exiting light from the waveguide to the outgoing optical fiber, which is connected to a THORlabs power meter to measure the output transmission.

Task 3: Assessment: The predicted resonant modes as a function of applied voltage of EOM will be compared to experimentally varying the voltage supplied to the crystal. Success will be measured through consistency to theoretical values while minimizing loss from the substrate and thermal intervention. Loss can be minimized by increasing the voltage and decreasing the mode cavity size, which decreases the number of available modes in the ring resonator, decreasing the size of the synthetic space. The number of modes in the frequency dimension where the group velocity is near-zero determines the size of the synthetic lattice. A happy compromise must be met in order to avoid damaging the resonator with too much voltage. The thermal properties of the system must also be controlled to minimize thermal drift. This will be maintained using a closed-cycle Helium cryostat. These properties of loss in the substrate and thermal drift must be mitigated or the resonant frequencies will vary dramatically.

Resources: Under the guidance of Dr. Mohammed Hafezi at my home institution, I will leverage the resources of the Joint Quantum Institute, the physics department at UMD, and the Hafezi group. I will use the University of Maryland's Raith e_LiNE to etch the patterns in the device, and its scanning electron microscope (SEM) imaging properties to view the device post-fabrication. The closed-cycle Helium cryostat belonging to the Hafezi group will be utilized to maintain the temperature of the device to below 3K, minimizing thermal drift. The design and simulation software will be Ansys Lumerical under the Hafezi group license. Large parameter sweeps will be performed in parallel using Zaratan, the University of Maryland's High-Performance Computing (HPC) cluster.

Intellectual Merit: One of the largest consequences of using synthetic dimensions is the ability to explore (N+1) dimensional physics in an N-D structure. Researchers have been able to use synthetic dimensions to simulate a whole host of phenomena, including 4D Quantum Hall Effect. This work helps generate exciting prospects, like simulating experimentally difficult quantum simulations in synthetic dimensions with the ring resonator on a photonic crystal. Synthetic dimensions have also been used to discover new phases of matter and new topological insulators. It is well established that in electronic and photonic systems, edge modes of topological insulators propagate without backscattering and time-reversal symmetry. Future focus can lie in the potential existence of these excitations with analogous properties in systems of atoms in these synthetic dimensional spaces.

Broader Impact: As computer chips shrink smaller and smaller, bulky 3-D photonic systems will be too large to be applicable for on-chip applications. However, using synthetic dimensions, we can utilize 1D and 2D photonic systems to replace those in 3D. This is important for the future of compact, integrated photonic devices and quantum emitters. Because only select wavelengths are allowed to propagate in these ring resonators, attaching multiple photonic ring resonators in succession can be used as a miniature add/drop filter. Using photonic systems with synthetic dimensions enhances speed, reduces energy consumption, increases reliability, and decreases space required for on-chip applications in advanced integrated photonic circuits and quantum systems.