# Snowmass2021 - Letter of Interest

# *Topological Microwave Circulators for HEP Applications*

**Thematic Areas:** (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (IF1) Quantum Sensors
■ (IF1) Cross Cutting and Systems Integration

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**Abstract:** (maximum 200 words)

The main challenge in detecting high-mass (frequency $>$ 10 GHz) axions through microwave cavity measurements is the suppressed scan rate in this high frequency regime. One promising option is to use multiple superconducting cavities that would allow hundreds of cavities to search simultaneously, therefore leading to an enhanced scan rate. Currently one of the major limitations of this scheme is the need to pack a large number of magnetic field sensitive devices, including microwave circulators and isolators, into a field free region. Here, we describe a new way of constructing miniaturized microwave circulators based on topological materials that can provide scalability to axion haloscopes and quantum sensing applications.[1]

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**Introduction**. Axion dark matter may be detected through the axion-photon-photon coupling in a microwave cavity under a strong magnetic field[1]. Recent microwave cavity experiments have made a significant progress in achieving the best possible sensitivity to axions of tens of $\mu$eV mass, or around 5 GHz[2,3]. However, searches for axions of higher frequencies while retaining the necessary sensitivity requires development of new microwave technologies. One promising approach is to use a multicavity array that is composed of large numbers (10s $\sim$ 100s) of individual cavities. The tuning range of each cavity can either be locked to a single frequency and coherently combined or they can have complementary frequencies generating a frequency comb that may have improved sensitivity and scan rate (both concepts are discussed in separate LOIs). Typically at least 3 microwave circulators are required in the quantum amplifier chain of a single cavity to protect the system from unwanted signals. This means that tens to hundreds of circulators have to fit within a small (typically a few liter) magnetic field free region in a low-temperature cryostat. While conventional microwave circulators are bulky, typically several centimeters in size[4], it would be important to develop geometry suppressed circulators.

In this letter of intent, we propose developing on-chip microwave circulators to meet the length scale requirements of an ADMX experiment through the synthesis of topological materials, development of device architecture, and modeling of system performance. Rather than using magnet and ferrite materials, novel quantum materials, time-reversal-symmetry breaking topological insulators, can be employed for realizing a microwave circulator with a tenth of a millimeter in size. The physics behind their nonreciprocal property is that electronic band structure topology enables this material to support robust chiral edge currents that flow either clockwise or counterclockwise around the boundary of the sample without resistance. The non-reciprocal characteristic of this materials system makes it an ideal platform for building an on-chip microwave circulator with zero insertion loss and zero magnetic field.

**Design mechanism**. The working principle of a topological circulator is based on the quantum anomalous Hall effect, which is defined as a novel manifestation of topological structure in many-electron systems. A topological circulator breaks reciprocity by combining the magnetic polarization and spin-orbit coupling in a topological insulator (TI) to generate a unidirectional transmission of signals in the absence of an external magnetic field . The development of a new topological quantum circulator is of practical importance to help control over quantum states with high fidelity across the quantum-classical interface. Our goal is to develop an on-chip chiral microwave topological circulator that yields a high degree of non-reciprocity and dynamic range, with the low insertion-loss inherent to the non-dissipative edge transport of a quantum anomalous Hall system. New microwave device design and characterization techniques together with novel topological materials synthesis and modeling will be developed cohesively to establish an effective approach to the invention of nonreciprocal topological devices. Connecting modeling and experiment through first-principle simulation and microwave circuit simulation capabilities will enable us to trace backwards from a desired device functionality to a candidate material and provide a better understanding of the roles played by magnetic defects, non-dissipative transport, and imperfection in the fabrication of microwave circuits across the nano-, micro- and mesoscales.

Central to the operation of our device is the capacitive coupling of microwaves into an isolated, etched disc of the magnetic topological insulator via edge magneto-plasmons. The mechanism of circulation can be understood as an interferometer (Fig. 1a), in which the topological insulator path through $C_{edge}$ is in phase with a capacitive path through $C_p$ in one direction, whereas out of phase in the reversed direction. One considerable challenge in this context arises because of the inherent impedance mismatch between the standard 50 $\Omega$ transmission line and the quantized one-dimensional edge channel characterized by a resistance of 25.4 k$\Omega$. The previous 3-port Carlin topological circulator used a LC matching circuit to transform a large series resistance towards 50 $\Omega$, however, the signal loss is still significant[5]. A creative route to overcome this challenge involves turning a 3-port Carlin circulator geometry (Fig. 1b) into a 2-

port gyrator device. We have modeled such a 2-port device by connecting the port 3 as a common ground between the operational ports 1 and 2 (See Fig. 2b). The coupling capacitance between the ports can be configured and the arc lengths of the ports can be tuned to achieve a self-impedance match at frequencies up to 5 GHz (Fig. 2c). Our circuit modeling effort will further reduce the insertion loss and guide experiments to design circuit parameters, providing a pathway to optimize circulator properties.

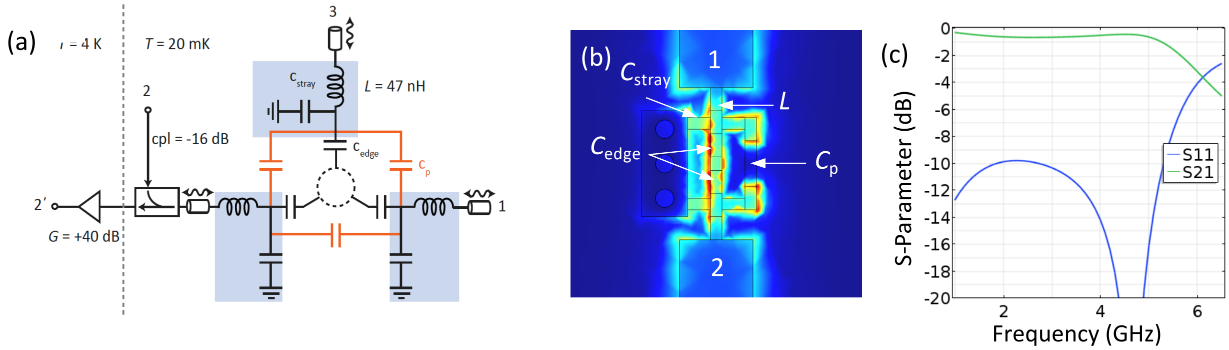

Figure 1: (a) Circuit schematic of the circulator[6]. (b) Electric field simulation of a two-port gyrator device at 4.3 GHz. (c) S-parameters of the impedance matched ports plotted as a function of frequency. The circuit ports are designed with a cutoff frequency at 5 GHz.

**Challenges**. We may face a challenge in optimizing the device performance that consists of a possible trade-off between the available signal bandwidth and the required drive power. To successfully understand and design such a device, we will first perform numerical simulation to model the circulator circuit, predict performance, and fabricate the topological circulators with both Cr-$(Bi,Sb)_2Te_3$ and $MnBi_2Te_4$ thin films[7]. Experimentally, a prototype device has been demonstrated in Cr-$(Bi, Sb)_2Te_3$ by our team member (Wang) at 0.02 K[6]. Recently, a new material $MnBi_2Te_4$ has been discovered to host robust chiral edge conduction at 1.6 K[8]. The 80 times temperature leap will potentially enhance the bandwidth of a topological circulator, as the limited bandwidth is one of the hurdles needed to be overcome before the device will be used for practical applications. Our team has significant research experience in material synthesis, microwave circuit design, device fabrication, condensed matter physics, and the first-principles calculation of the anomalous Hall effect, capable of performing the proposed tasks for this project.

**Conclusion**. Upon successful completion of this project, the key factors that influence the metrics of a topological circulator will be well understood and topological materials with targeted functionality will be demonstrated. We expect the second-generation low loss TC can achieve a spectral bandwidth of over 2 GHz and an isolation of over 22 dB. New topological materials hold the promise for the zero-field operation of microwave circulators and the reduction in the size of a multicavity systems for axion dark matter searches.

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## Additional Authors:

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