Trembling Photons in Non-Abelian Electric Fields

A ring of optical fiber can be made to host phenomena that originated in the realm of high-energy physics.

By **Xin Qiao** and **Xiao-Bo Zhang**

In non-Abelian gauge theories, particles interact with each other; operation order matters; and a so-called gauge symmetry ensures the invariance of physical laws under local transformations via fields mediated by photons, gluons, and the *W* and *Z* bosons. Such theories describe the strong and weak forces; provide the mathematical backbone of the standard model; and underpin efforts to understand the early Universe, quantum gravity, and exotic topological phases of matter. For decades, subjecting these theories to direct experimental scrutiny often meant resorting to enormous particle accelerators. Recently, an experimental approach known as photonic synthetic dimensions has offered a tabletop alternative. Applications of the approach have already realized a non-Abelian magnetic field [**1**]. Now Shu Yang of the University of Hong Kong and his colleagues have synthesized the corresponding non-Abelian electric field [**2**]. Specifically, the researchers' all-optical platform has enabled the creation of a central element of non-Abelian gauge theories: the Yang-Mills field tensor. Physics that once belonged to the realm of high-energy theory alone is now firmly established in photonics experiments.

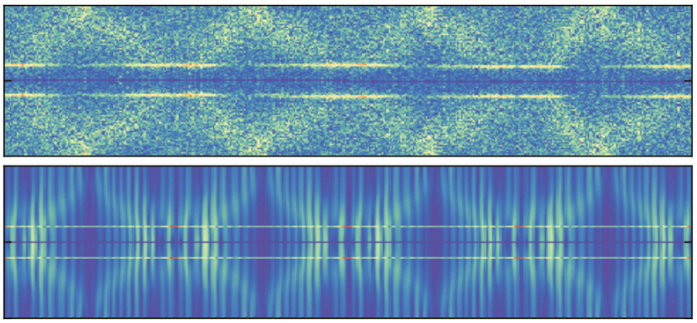

Figure 1: An optical pulse injected into the ring interacts with the non-Abelian electric field to set off the trembling motion known as *Zitterbewegung*. Modulating the pulse activates an Abelian electric field that sets off Bloch oscillations. The observation (top) and the simulation (bottom) show that the coexistence of the two fields leads to interferences between the *Zitterbewegung* and the Bloch oscillations.
Credit: S. Yang *et al.* [**2**]

Yang and his colleagues achieved their feat using a platform based on fiber ring resonators, in which light resonates at a series of equally spaced discrete frequencies. When driven by an electro-optic modulator matched to the cavity's free spectral range, photons coherently hop between adjacent frequency modes. The hopping establishes an effective lattice with tunable intersite couplings [**3**–**5**]. Such a lattice has two distinctive and advantageous properties. First, it's highly programmable. The intersite coupling strengths are fully determined by external electrical modulation, enabling real-time, flexible manipulation of lattice hopping without the need to restructure the device. By contrast, the structure of a conventional photonic lattice is fixed by the fabrication process. The second beneficial property is the ability to incorporate multiple degrees of freedom. These include polarization (which serves as the pseudospin in this setup), orbital angular momentum, and optical delay, which can all be adjusted to construct complex high-dimensional lattices.

Maxwell's equations constitute an Abelian theory in which field strengths depend only on the spatial and temporal derivatives of their two gauge potentials: the electric scalar potential and the magnetic vector potential. The theory's non-Abelian

counterpart expands this framework. Electromagnetic fields gain extra contributions from the noncommutativity of the scalar and vector potentials, enabling electric-field generation under spatially homogeneous and temporally static potentials. In their new experiment, Yang and his colleagues engineered a non-Abelian field with a ring resonator that was polarization multiplexed and time modulated. Three controls brought the gauge structure into being inside the ring.

Polarization-dependent phase modulation realized the vector potential, while polarization rotation and polarization retardation jointly realized the scalar potential [**6**]. Thanks to the noncommutativity between the scalar and the vector potentials, the resulting electric field was purely non-Abelian, corresponding to the electric component of the Yang-Mills field strength tensor. Because ring resonators are effectively one-dimensional, non-Abelian magnetic fields are absent for lack of flux, leaving the electric field as the tensor's sole observable signature.

Yang and his colleagues found that the non-Abelian character of the synthetic electric field was also manifested in the system's Floquet band structure—that is, the set of energy levels that emerge when a system is periodically driven. By independently tuning polarization rotation and phase retardation, the researchers manipulated both the energy-band dispersion and the momentum-resolved spin textures. Varying only the rotation angle transformed the lower band from a double well to a single well. Introducing phase retardation lifted the ground-state degeneracy and swapped the spin polarization of the two bands. In Abelian gauge fields, scalar potentials induce only energy shifts. By contrast, Yang and colleagues' non-Abelian system strongly coupled spin configurations to band structures.

The time domain is also where another manifestation of the non-Abelian electric field appeared. Yang and colleagues traced the spectral evolution of an optical pulse injected into the ring. When they did so, they observed *Zitterbewegung*: the oscillation of the center of mass of a wave packet along the frequency axis caused by the noncommutativity of the scalar and vector potentials. This trembling motion (a direct translation of the original German) is the photonic analogue of the relativistic jittering predicted for Dirac electrons. It persists without requiring spectral detuning, spatial gradients, or time-dependent external driving. But when modulation detuning is introduced, an Abelian electric field is activated and Bloch oscillations—the bouncing back and forth of particles in a periodic lattice—appear. The coexistence of non-Abelian and Abelian electric fields causes the *Zitterbewegung* and the Bloch oscillations to interfere (Fig. **1**).

Yang and his colleagues' experiment opens several promising avenues for future exploration and practical applications. Their fiber-ring-based three-control architecture is directly compatible with thin films of lithium niobate, a transparent, nonlinear crystal with myriad photonic applications [**7**]. Programmable non-Abelian circuits could be fashioned on chip-scale platforms to harness the interference between *Zitterbewegung* and Bloch oscillations. For example, the interference could enable reconfigurable frequency-domain signal processing by jointly steering the polarization texture and the spectral distribution of multiplexed frequency combs. What's more, because the frequency-dimension system naturally interfaces with fiber networks, these functionalities could be integrated, loss-free, into existing telecommunication infrastructure.

Now that both the electric and magnetic components of the Yang-Mills field tensor have been realized in photonic synthetic dimensions, the platform's programmability and polarization control could open several major research directions. Already, the platform has been used to realize a non-Abelian gauge theory that is open to the gain or loss of energy [**8**] and one that is relevant to quantum gravity [**9**]. The same platform could host non-Abelian band topology and symmetry-protected non-Abelian phases. If the coherent detection demonstrated by Yang and his colleagues could be extended to the quantum level, the simulation of a vital ingredient of fault-tolerant topological quantum computing—anyon braiding—could be within reach.

Xin Qiao: College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou, China

Xiao-Bo Zhang: College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou, China

REFERENCES

1. D. Cheng *et al.*, "Non-Abelian lattice gauge fields in photonic

synthetic frequency dimensions," **Nature 637, 52 (2025).**
2. S. Yang *et al.*, "Non-Abelian electric field and *Zitterbewegung* on a photonic frequency chain," **Phys. Rev. Lett. 137, 056901 (2026).**
3. L. Yuan *et al.*, "Synthetic frequency dimensions in dynamically modulated ring resonators," **APL Photonics 6, 071102 (2021).**
4. A. Dutt *et al.*, "A single photonic cavity with two independent physical synthetic dimensions," **Science 367, 59 (2020).**
5. D. Yu *et al.*, "Comprehensive review on developments of synthetic dimensions," **Photonics Insights 4, R06 (2025).**
6. B. T. T. Wong *et al.*, "Synthetic Non-Abelian electric fields and spin-orbit coupling in photonic synthetic dimensions," **Phys. Rev. Lett. 134, 163803 (2025).**
7. H. X. Dinh *et al.*, "Reconfigurable synthetic dimension frequency lattices in an integrated lithium niobate ring cavity," **Commun. Phys. 7, 185 (2024).**
8. Z. Pang *et al.*, "Synthetic Non-Abelian gauge fields for non-Hermitian systems," **Phys. Rev. Lett. 132, 043804 (2024).**
9. Z. Dong *et al.*, "SL(2, $\mathbb{C}$) non-Abelian gauge fields in a photonic molecule array," **Nat. Commun. 16, 10166 (2025).**