Real-time observation of frequency Bloch oscillations with fibre loop modulation

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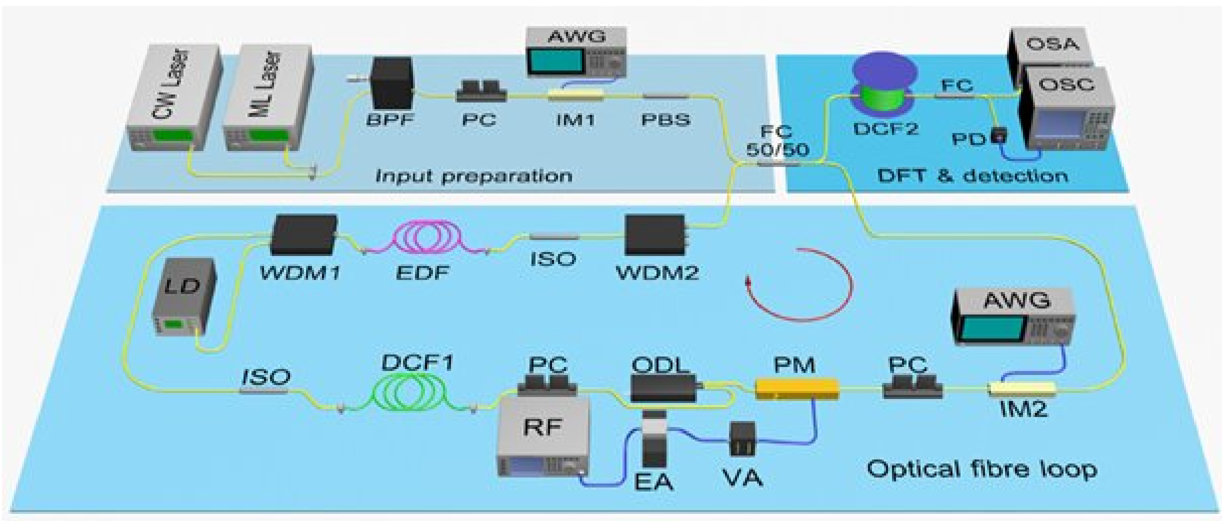


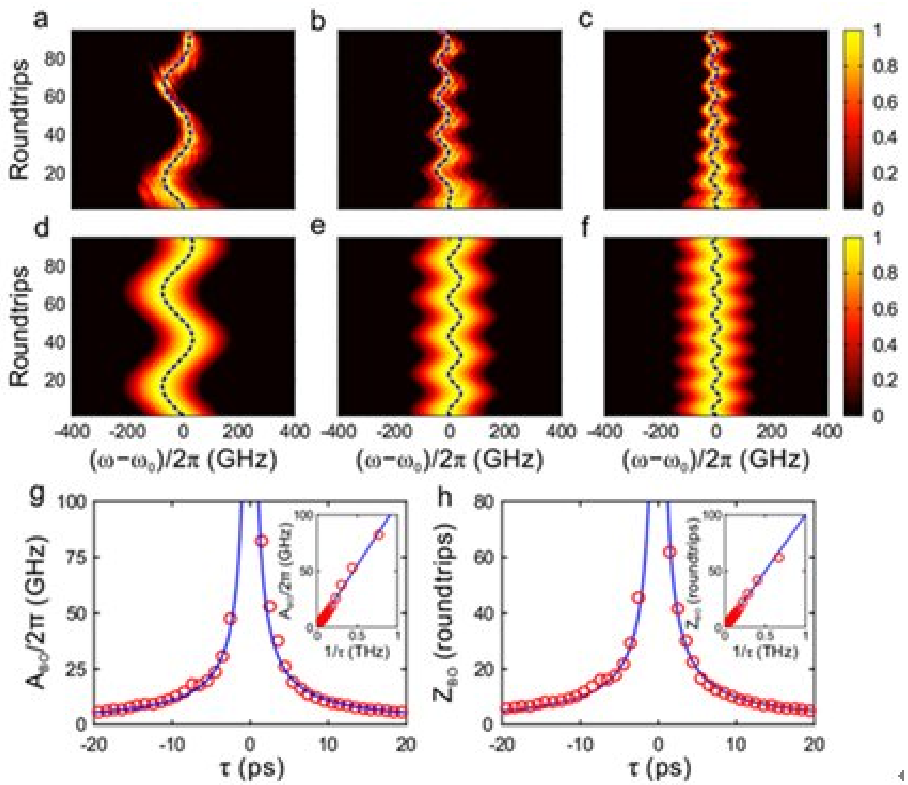
CW Laser, continuous-wave laser; ML Laser, mode-locked laser; BPF, bandpass filter; PC, polarization controller; AWG, arbitrary waveform generation; IM, intensity modulator; PBS, polarization beam splitter; FC, fibre coupler; RF, radio-frequency signal generator; EA, electrical amplifier; VA, variable attenuator; ODL, optical delay line; DCF, dispersion-compensating fibre; ISO, isolator; LD, laser diode; WDM, wavelength-division multiplexer; EDF, erbium-doped fibre; PD, photodetector; OSC, oscilloscope; OSA, optical spectrum analyser. Credit: Hao Chen, NingNing Yang, Chengzhi Qin, Wenwan Li, Bing Wang, Tianwen Han, Chi Zhang, Weiwei Liu, Kai Wang, Hua Long, Xinliang Zhang and Peixiang Lu

Bloch oscillations (BOs) were initially predicted for electrons in a solid lattice as a static electric field is applied. Scientists in China created a synthetic frequency lattice in a fiber loop under detuned phase modulation and directly observed the frequency BOs in real time. The frequency spectrum in telecommunication band can be shifted as large as hundreds of GHz. The study may find applications in frequency manipulations in optical fiber communication systems.

BOs describe the periodic movement of electrons in solids to which an external static electric field is applied. However, it is challenging to measure the BOs directly in natural solids since the relaxation time of electrons is usually much shorter than the oscillation period. To date, analogies of electron BOs have been extended to the synthetic dimensions of time, frequency and angular momenta.

In previous studies, the frequency BOs have been experimentally demonstrated in a nonlinear fiber with cross-phase modulation. However, the frequency spectrum has been obtained only at the output of the fiber, and thus the evolution process of BOs has been measured only indirectly. In addition, frequency BOs have been theoretically demonstrated in micro-resonators under temporal modulation. Considering the compact structure of ring resonators, the direct observation of BOs still faces difficulties in compensating for the power reduction when collecting signals.

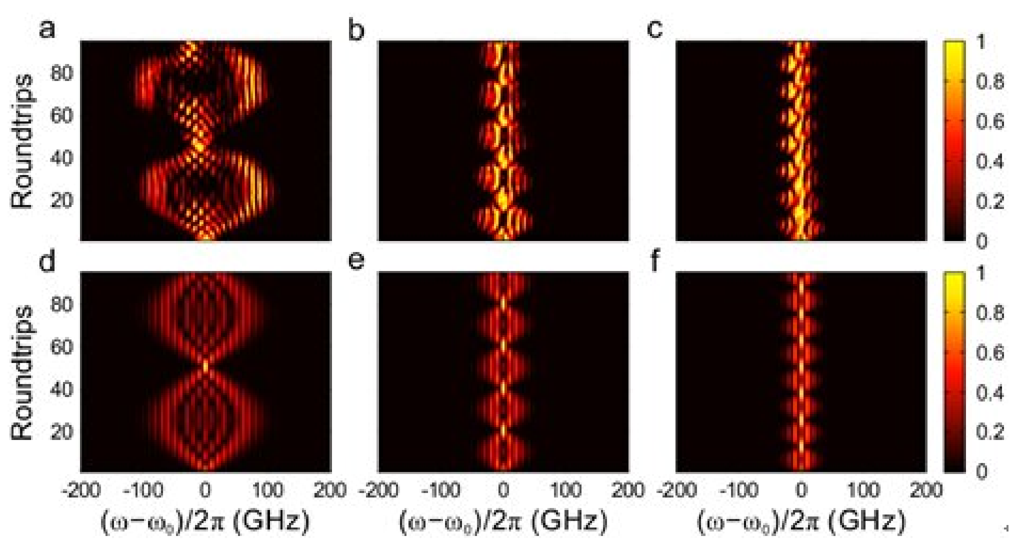
In a new paper published in *Light Science & Applications*, a team of scientists, led by Professor Bing Wang from School of Physics and Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, China, and co-workers have directly observed the frequency BOs in a modulated fiber loop with time detuning. The spectrum of the incident optical pulse experienced a periodic movement in the frequency lattice formed by the phase modulation. The time detuning produced an effective electric-field force in the lattice, which was associated with the effective vector potential varying with the spectrum evolution. Additionally, the transient evolution of the spectrum was measured in real time by using the dispersive Fourier transformation (DFT) technique. Based on the frequency-domain BOs, a maximum frequency shift up to 82 GHz was achieved. The bandwidth of the input pulse was also broadened up to 312 GHz.



a-c Experimental results of the frequency BOs under a time detuning of 2, 5 and 8 ps. d-f Simulated BOs corresponding to the experimental results in a-c. g, h Amplitude and period of the BOs as a function of the time detuning. Credit: Hao Chen, NingNing Yang, Chengzhi Qin, Wenwan Li, Bing Wang, Tianwen Han, Chi Zhang, Weiwei Liu, Kai Wang, Hua Long, Xinliang Zhang and Peixiang Lu

The study offers a promising approach to realizing BOs in synthetic dimensions and may find applications in frequency manipulations in optical fiber communication systems. These scientists summarize the principle of the work: "The phase modulation induces the coupling between the adjacent frequency modes which constructs a lattice in the frequency dimension. As the optical pulse propagates in fiber loop, the roundtrip time can be adjusted by using an optical delay line. A small time detuning can be introduced between the pulse circulation time and modulation period, which serves as an effective electric-field force in the frequency lattice and thus land thus gives rise to frequency BOs. We show that the vector potential can also contribute to generation of the effective force, which varies with the propagation distance."

"To realize real-time measurement of the pulse spectrum coupled out from the loop, a spectroscope based on the DFT is connected at the end of the fiber-loop circuit. A long dispersion-compensating fiber performs a Fourier transform, which maps the spectrum envelope of the optical pulse into a time-domain waveform. Thanks to the dispersion in fiber, real-time measurement of the frequency spectrum with a resolution of ~9.8 GHz can be achieved."



a-c Experimental spectrum evolution with time detuning of 2, 5 and 8 ps, respectively. d-f Numerical results corresponding to a-c. Credit: Hao Chen, NingNing Yang, Chengzhi Qin, Wenwan Li, Bing Wang, Tianwen Han, Chi Zhang, Weiwei Liu, Kai Wang, Hua Long, Xinliang Zhang and Peixiang Lu

"We implement the incidence of both short and broad pulses and directly observe the oscillating and breathing modes of frequency BOs. As the short pulse propagates in the fiber loop, one sees that the spectrum of the incident pulse evolves along a cosinoidal trajectory, referring to frequency BOs. For a broad pulse, the spectrum manifests a breathing pattern accompanied by a self-focusing effect during evolution," they added.

"Based on the present method, the spectrum manipulations overcome the microelectronic bandwidth limitation. This study may find many applications in high-efficiency frequency conversion and signal processing. Additionally, in the aid of BOs, we verified that the vector gauge potential can be employed to manipulate the optical properties of photons in synthetic frequency lattice, which provides a unique way to control light, especially in the field of topological photonics," the scientists predict.

More information: Hao Chen et al, Real-time observation of frequency Bloch oscillations with fibre loop modulation, *Light: Science & Applications* (2021). DOI: 10.1038/s41377-021-00494-w

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