

Phase matching sampling algorithm for sampling rate reduction in time division multiplexing optical fiber sensor system

The PMS algorithm for greatly reducing the sampling rate is expected to fuel the TDM interferometric sensor arrays for many applications.

CHENGDU, SICHUAN, CHINA, October 24, 2025 /EINPresswire.com/ -- As one of the cutting-edge research areas in modern physics, space-based [gravitational wave detection](#) aims at capturing gravitational wave signals in the mHz frequency band. A key technological challenge in such missions lies in establishing a high-precision spatial inertial reference, which requires monitoring the six-degree-of-freedom (6-DoF) motion of the test mass within the mHz frequency range. [Fiber-optic interferometric](#) time-division multiplexing (TDM) sensing systems offer significant advantages such as high sensitivity, immunity to electromagnetic interference, light weight, and ease of installation, making them highly promising for application in measuring the 6-DoF motion of the test mass.

The core challenge in applying TDM fiber-optic [interferometric sensing systems](#) to space-based gravitational wave detection is to maintain comparable phase resolution in the mHz band from a multiplexed sensor to that of a singular sensor. However, if conventional data acquisition methods are used, improving phase accuracy typically requires narrowing the optical pulse width to reduce the length of the delay fiber. Nevertheless, reducing the pulse width leads to a higher frequency of the carrier signal, which in turn demands a higher data acquisition rate. This results in issues including increased power consumption and large data volumes, posing practical

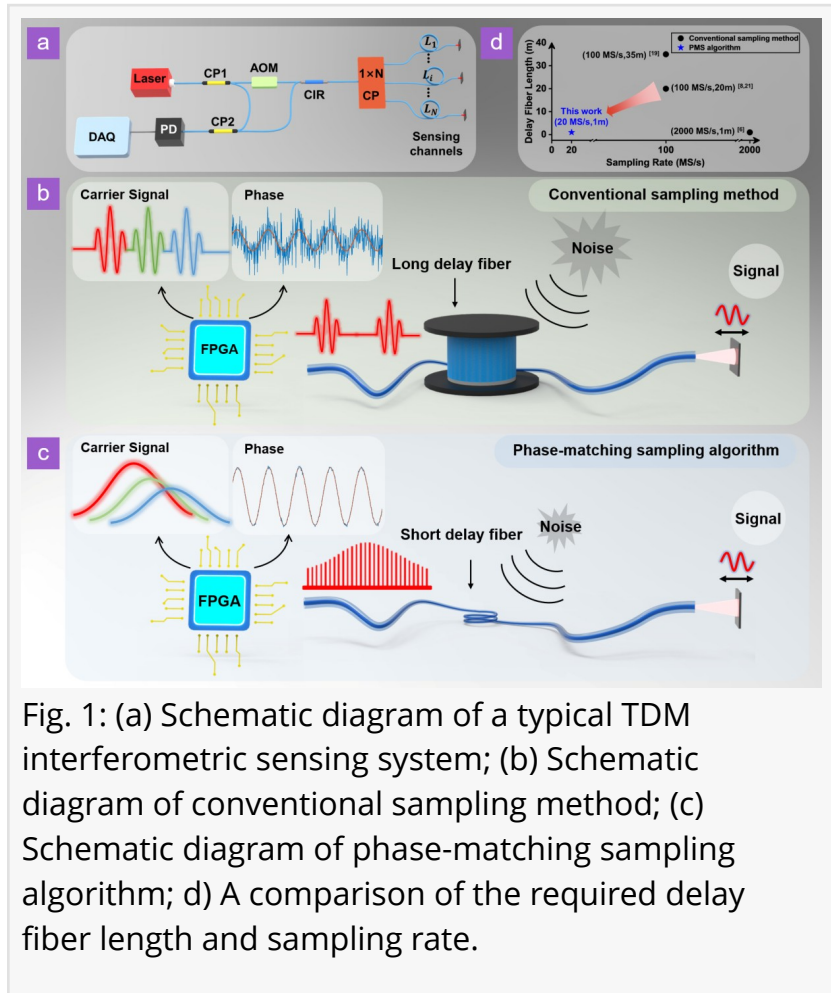


Fig. 1: (a) Schematic diagram of a typical TDM interferometric sensing system; (b) Schematic diagram of conventional sampling method; (c) Schematic diagram of phase-matching sampling algorithm; (d) A comparison of the required delay fiber length and sampling rate.

limitations for real-world applications. Therefore, there is an urgent need to innovate data acquisition and processing algorithms to overcome the constraints imposed by sampling rates and delay lengths in TDM fiber-optic interferometric sensing systems.

About the Research Group:

The research group led by Associate Researcher Zhilin Xu and Professor Qizhen Sun from Huazhong University of Science and Technology has proposed a phase-matching sampling method that effectively resolves the mutual constraints between sampling rate and delay fiber length in TDM fiber-optic interferometric systems. The main innovative idea of this method is to set the carrier signal period significantly longer than the optical pulse width, so that each optical pulse carries only partial carrier information of the corresponding sensing channel. The complete carrier signal of each channel is then reconstructed by combining multiple optical pulses. This approach significantly reduces the carrier signal frequency even with short delay fibers and narrow pulse widths, thereby lowering the sampling rate.

To achieve this, the phase-matching sampling method divides the sampling clocks into multiple groups, with each group containing the same number of sampling clocks as the number of sensing channels. The phase delay of each clock within a group is matched to the delay fiber length of the corresponding sensing channel, ensuring that the i -th clock samples only the optical pulse reflected by the i -th sensing channel. Through cyclic sampling across multiple clock groups, the complete carrier signals of all sensing channels are sequentially reconstructed.

Theoretical analysis shows that, under equivalent measurement performance, the required sampling rate can be reduced from the GS/s level to tens of MS/s, and the delay fiber length can be shortened from hundreds of meters to just a few meters. This drastically reduces data



Fig. 2: (a) and (c) Schematic diagram and ADC clock phase of the conventional sampling method; (b) and (d) Schematic diagram and ADC clock phase of the proposed PMS algorithm.

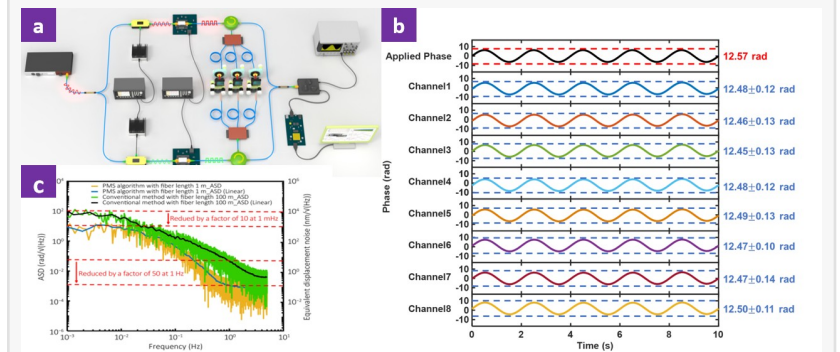


Fig. 3: (a) Schematic diagram of the 8-channel TDM interferometric displacement sensing system; (b) Phase of each sensing channel demodulated from the data recovered by the proposed PMS algorithm; (c) The phase phases ASD....

resource consumption while also improving the phase measurement accuracy of multi-channel fiber-optic interferometric displacement sensing system.

To validate the signal reconstruction capability and measurement accuracy of the phase-matching sampling method, the researchers constructed an 8-channel heterodyne interferometric displacement sensing TDM system (Fig. 3). Using data acquired via the proposed method, the demodulated phase error was only 0.95%, and the displacement measurement error was below 0.25%. Compared with the conventional sampling method, the phase noise floor of the system was reduced by 50 times at 1 Hz. The proposed phase matching sampling algorithm paves the way for high-precision multiplexed fiber-optic interferometric sensing systems, with significant application potential in space gravitational wave detection, low-frequency underwater acoustic monitoring, and geophysical exploration.

About the Authors:

Zhilin Xu is an Associate Researcher at the National Gravitation Laboratory, Huazhong University of Science and Technology. She has led or participated in multiple research projects, including those funded by the National Natural Science Foundation of China and the National Key Research and Development Program specializing in gravitational wave detection. Her research primarily focuses on optical fiber sensing and precision measurement, achieving sub-picometer-level displacement resolution and sub-nanogram-level vibration sensitivity in the very low frequency range of 0.1 Hz. Dr. Xu has published over 40 papers in authoritative journals such as Opto-Electronics Technology, Optica, and IEEE Journal of Lightwave Technology, and has applied for or been granted more than 10 invention patents.

Qizhen Sun is a national high-level talent and serves as Professor and Vice Dean at the School of Optical and Electronic Information/School of Future Technology, Huazhong University of Science and Technology. She also holds several key positions, including Chair of the IEEE Sensors and Systems China Special Committee, Council Member of the Chinese Society of Optical Engineering, and Director of the Hubei Provincial Engineering Research Center for IoT Access.

Her primary research focuses on fiber optic sensing technologies and their applications. She has led multiple major research projects, including those under the National Key R&D Program of China, and projects supported by the National Natural Science Foundation of China, such as the Distinguished Young Scholars Program, Excellent Young Scholars Program, and Regional Joint Key Projects.

Professor Sun has published over 120 papers in internationally renowned journals such as Light: Science & Applications, Opto-Electronics Advances, Nature Communications, Photonix, Advanced Science, and Optica. She holds 47 authorized invention patents and 4 software copyrights, and has contributed to the development of 4 national/military standards and 2 group standards. Her research achievements have been recognized with 8 scientific awards, including the First Prize of Hubei Provincial Technology Invention Award and the First Prize of Technical Invention Award from the China Institute of Communications.

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