Interferometric Fiber Optic Sensors

Subjects: Others
Contributor: Weimin Lyu

Due to the improvement of living standards, people's attention to health has gradually increased. More and more people are willing to spend money and time on health management. The vital signs monitoring system based on fiber optic interferometers, including the design of sensor structures, signal demodulation methods and data analysis. After a large number of trials, the system can achieve long-term stable heart rate (HR), respiration rate (RR) and body temperature monitoring, and the collected data can be used for health analysis. Due to the high sensitivity, low cost, and light weight of the interferometric fiber optic sensor, it can be integrated under a mattress or a cushion, which is very suitable for daily use. The system has great application prospects in the field of healthcare.

optical fiber interferometers | vital signs monitoring | demodulation schemes | heart rate analysis

1. Introduction

In recent decades, with economic development and social progress, people's health awareness has gradually increased, and more and more attention has been paid to medical care. Daily health tracking can enable people to understand their physical condition. Heartbeat, respiration, body temperature, blood pressure (BP), blood oxygen, etc. are all important health indicators of the human body. Among the various vital sign parameters, heartbeat and respiration are particularly important; they are closely related to a variety of senile diseases, such as chronic obstructive pulmonary disease and congestive heart failure [1]. In areas where the population is seriously aging and medical resources are scarce, monitoring equipment for vital signs is particularly necessary. Many schemes for measuring vital signs signals have been developed in recent decades. In the current medical system, an electrocardiogram (ECG) is the most widely used heart health monitoring method [2]. Through multiple electrodes attached to the body, it can record the electrical activity signals of the heart. For respiratory monitoring, spirometer, capnometry and impedance pneumography are the most used methods [3]. However, a spirometer can interfere with natural breathing, making continuous RR monitoring difficult. The capnometry method can also cause discomfort due to the contact required. Impedance pneumography requires special equipment for analysis. Therefore, these heartbeat and breathing monitoring devices are not suitable for daily household use. Ballistocardiography (BCG) is another cardiac measurement technique, which reflects the mechanical information of the heart, and there is no need to stick any patches on the body during measurement. It is hopeful that it can be used as a substitute for an ECG in the consumer field. In addition, respiration can also be extracted from the BCG signal detected while in the sitting or lying position. Using the difference in the frequency of heartbeat and respiration, it is possible to monitor both HR and RR through one monitoring system.

In the past decade, many non-wearable vital signs monitoring programs have emerged. For example, G. Vinci et al. proposed a vital signs monitoring program based on the six-port interferometer radar principle, which can detect the subject's respiration and heartbeat from the reflected original radar signal [4]. D. Shao et al. used a single camera to track the movement of facial features to obtain BCG [5]. This method can also obtain photoplethysmography (PPG) based on the reflected light from the same facial area. Hassan et al. obtained the BCG signal by measuring the head movement caused by the heart blood ejection and estimated the heartbeat by calculating the movement of multiple feature points [6]. However, these methods also have some limitations. Radar-based systems are easily affected by electromagnetic interference (EMI). Camera-based systems are susceptible to motion artifacts and may introduce privacy issues.

Fiber optic sensors (FOS) can avoid the problems of the above-mentioned sensors, and have high sensitivity; therefore, they are attracting a lot of attention [7]. Researchers have proposed many different options for monitoring vital signs. Z. Chen et al. proposed and demonstrated the feasibility of using a microbend multimode fiber optic sensor for the simultaneous measurement of HR and RR [8]. A.G. Leal-Juniora et al. developed a sensor based on polymer optical fiber, which is embedded in the user's clothes as a smart textile solution that can be used to measure breathing rate and HR at the same time [9]. Their intensity-based sensors can measure HR and breathing rate, but they are not as sensitive as wavelength-based sensors. Ł. Dziuda et al. used an optical strain sensor based on fiber Bragg grating, monitoring the respiration and cardiac activity of a patient during magnetic resonance imaging (MRI) [10]. S. Koyama et al. proposed a sensor based on plastic FBG to measure vital signs such as pulse rate and BP [11]. Under the same applied pressure, the plastic FBG sensor deforms more than the silica glass FBG sensor, and the Bragg wavelength shift length becomes longer, which results in higher detection sensitivity. However, the cost of FBG-based sensors is too high and not suitable for widespread use. Due to the high cost of the FBG sensors and the limited sensitivity of the intensity-based sensors, researchers chose the interferometric FOS for vital signs monitoring.

2. Structures and Principles of Interferometric FOS

The work of the interferometer used for vital signs monitoring is caused by the interference of two light beams, which propagate through one or more optical fibers by different optical paths. Beam splitting and beam combining are often realized by couplers. There are four types of interferometers, which are Fabry–Pérot, Mach–Zehnder, Michelson and Sagnac interferometers. The following will describe their main characteristics and differences in their applications as optical fiber sensors.

2.1. Optical Fiber Mach–Zehnder Interferometer

The Mach–Zehnder interferometer (MZI) is mainly composed of two 3 dB couplers and several sections of single-mode fiber (SMF). The sensor structure is shown in **Figure 1**a. When the sensing system is working, the laser injected from one end is divided into two beams of equal intensity through the first coupler, entering the reference arm and the sensing arm, respectively, and then recombining through the second coupler. Since the difference in the length of the two arms is introduced in the manufacturing process of the sensor, there is a phase difference when the two beams of light meet at the second coupler. For sensing, the reference arm is kept isolated from any external changes as much as possible while the sensing arm feels the influence of external changes. External factors (temperature, pressure, etc.) can directly cause changes in the length and refractive index of the optical fiber sensing arm of the MZI. In the end, the change of the interference signal comes from the optical path difference, and the photodetector (PD) can be used to detect these changes.

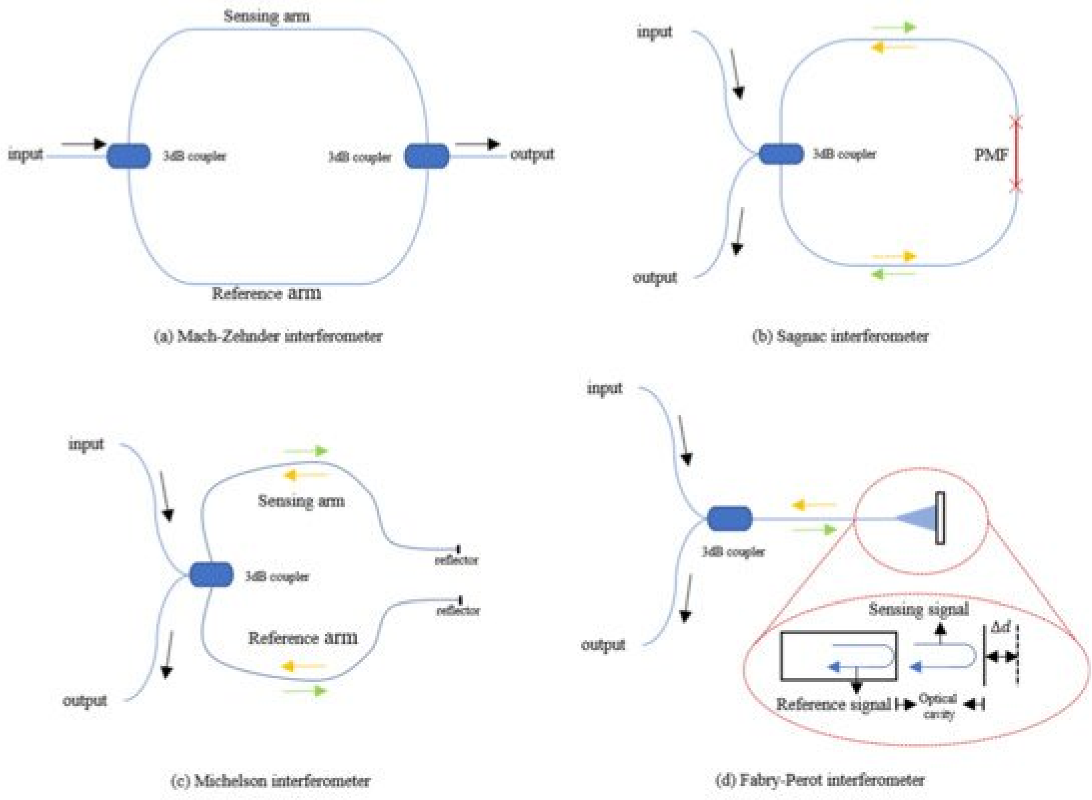

Figure 1. (**a**) Structure of optical fiber Mach–Zehnder interferometer; (**b**) Structure of optical fiber SI based on PMF; (**c**) Structure of optical fiber Michelson interferometer; (**d**) Structure of optical fiber Fabry–Perot interferometer.

As mentioned above, the arm length difference was introduced when the sensor was manufactured. W. Lyu et al. have conducted a lot of research on FOS for vital signs detection based on MZI [12][13][14]. After experimental testing, when the ΔL of FOS based on MZI is 5 mm, its free spectral range can achieve satisfactory results in actual use. The length of the sensing arm and reference arm can range from 60/60.5 cm to 200/200.5 cm to obtain a good BCG signal, depending on the size and purpose of the sensor.

In addition to the traditional MZI, F. Tan et al. proposed in-line interferometers based on few-mode fiber (FMF) and multi-core fiber (MCF) for vital signs monitoring [15]. The structure of the FMF interferometer is to use two sections of SMF spliced at both ends of the FMF, as shown in **Figure 2**a. The offset between SMF and FMF is used for mode excitation to form mode interference. The researchers have conducted research on both two-mode fiber and four-mode fiber, and compared the spectra under different offset distances. Considering the extinction ratio and the insertion loss with offset distance, the size of the in-line interferometer is optimized. SMF will be spliced on both ends with the best offset distance. Both FMF-based sensors can simultaneously achieve HR and RR monitoring with acceptable accuracy. C. Ke et al. applied this structure for the same purpose [16]. They used the multimode between two single-mode fibers and obtained satisfactory results. R. Wang et al. used an FMF-based interferometer to focus on the analysis of respiration, such as RR, tidal volume (TV) and minute ventilation (MV) [17].

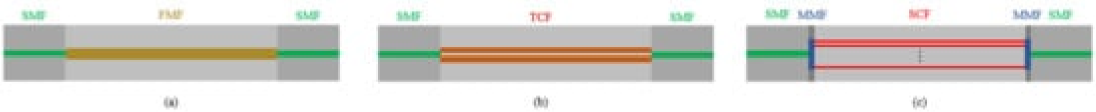

Figure 2. (**a**)The schematic diagram of FMF in-line interferometers based on the structure of SMF-FMF-SMF; (**b**) the schematic diagram of TCF in-line interferometer based on SMF-TCF-SMF; (**c**) the schematic diagram of SCF in-line interferometer based on the structure of SMF-MMF-SCF-MMF-SMF.

For the MCF interferometer, F. Tan et al. employed twin-core fiber (TCF) [18], and W. Chen et al. adopted seven-core fiber (SCF) [19]. The structures are shown in **Figure 2**b,c, respectively. Based on the coupling mode theory, power exchange occurs between the cores in the MCF. This kind of crosstalk between cores can be explained by supermodel theory. Due to the difference in propagation constants, the coupling characteristics between supermodes can be used to develop FOS with excellent performance. In the SCF, a section of multimode fiber (MMF) is spliced between the SMF and SCF at the incident end to expand the light field and excite all the cores in the SCF. A section of the same MMF is spliced at the output end to collect light from the SCF into the SMF and obtain the mode interference spectrum. For the two cores of TCF, inter-mode interference will also occur. Sensors based on this principle are very sensitive to small pressure changes in the vertical direction of the two cores. The ideal frequency spectrum for vital signs monitoring was obtained through various experiments. J. Zhang et al. used a TCF-based sensor to measure the human body's BCG and breathing signals after exercise and analyzed the HR changes during the 3-min recovery process [20]. W. Chen et al. used the SCF to develop a sensor for HR and RR monitoring with a small size and high sensitivity [19]. In their experiment, the HR and RR measurement results between the proposed sensor system and the reference monitor are in good agreement, and the SD is 1.17 beats per minute and 2.16 breaths per minute, respectively.

For TCF, because it can achieve better performance, F. Tan et al. have conducted further research [18]. Since the two cores are very close, they will exchange power, which can be described by supermodel theory. In the sensor production process, a slight offset was introduced between SMF and TCF to obtain a better frequency spectrum. Detailed experiments have been carried out on the offset direction between SMF and TCF and the spectra at different offset distances from 0 to 10 μm. In addition, the length of TCF has also been optimized through experiments. After comparing the output spectra under different offset distances and the length of TCF, the optimal offset distance and the length of TCF are determined and used to monitor vital signs after exercise.

2.2. Optical Fiber Sagnac Interferometer

The structure of the Sagnac interferometer (SI) is shown in **Figure 1**b. The basic principle is to detect the different phase shifts of the two beams of light transmitted in opposite directions through the interference effect under the action of external factors. The beam enters the coupler through one end of the fiber, and then splits into two beams with the same intensity. The two beams of light move in opposite directions through the fiber and return to the coupler to interfere. This kind of interferometer has high sensitivity to rotation and is mainly used in fiber optic gyroscopes. J. Qu et al. conducted some research on the use of SI-based sensors for vital signs monitoring [21]. Since this situation cannot introduce the rotation of the sensor, the sensor introduces a phase difference through a single-mode polarization-maintaining fiber (PMF) inserted into the Sagnac loop. Due to the special structure of PMF, it has two polarization modes, including vertical and horizontal polarization modes. The phase velocities of these two modes are slightly different, therefore, the light will have a phase difference during transmission. In the interferometer, the incident light of the laser is split into two opposite beams by a 3 dB coupler and propagates in the SI. After passing through the PMF, a phase difference between the two beams is formed, and finally, they interfere when they return to the 3 dB coupler. The interference signal received by a PD at the end includes heartbeat and respiration information. C. Ke et al. applied this structure in their smart mattress to detect vital signs. The small difference is that their SI uses SMF and dispersion-shifted fiber [22]. To achieve better performance, J. Qu et al. have carried out related experiments on the impact of PMF of different lengths on vital signs signals. Insert PMF with lengths of 0.5, 1.5 and 2.5 m into the Sagnac loop, and observe the change in sensor sensitivity.

2.3. Optical Fiber Michelson Interferometer

FOS based on the Michelson interferometer (MI) can also be used to monitor vital signs, and the structure is similar to MZI, as shown in **Figure 1**c. The 3 dB coupler connects the laser and PD on one side with the sensing and reference arm, and the other side of the two arms is covered with silver. The manufacturing method and working principle of MI are almost the same as MZI because it is almost half of MZI in configuration. The main difference is whether there is a reflector on the arms. As MI adopts reflection mode, it is compact and convenient in experimental use. However, the difference in fiber length between the two arms of the MI must be adjusted within the coherence length of the light source. D. Zazula et al. used Morlet wavelet-based transform to separate BCG and phonocardiographic (PCG) components of the heart activity detected by a MI FOS [23]. S. Šprager et al. realized high-sensitivity and high-precision HR signal detection through the same principle [24].

2.4. Optical Fiber Fabry-Perot Interferometers

The fiber Fabry–Perot Interferometer (FFPI) is also a practical solution for vital signs monitoring, and its structure is shown in **Figure 1**d. The core component is an optical cavity composed of a pair of parallel reflecting surfaces with a distance of several micrometers to centimeters. After the incident light passes through the 3 dB coupler, it passes through the optical fiber to reach the cavity. Part of the light is reflected back at the end of the fiber cavity as a reference signal, and the rest of the light is reflected after passing through the cavity. The two beams of reflected light pass through the optical fiber and interfere in the coupler. The output interference signal is related to the length of the microcavity.

S. Pullteap et al. have developed a high-sensitivity vital signs monitor based on FFPI to measure two interesting parameters, HR and BP [25]. Compared with medical digital sphygmomanometers, the average error of systolic and diastolic blood pressure and HR measured by the FFPI sensor is less than 2%. P. Samartkit et al. investigated an FFPI-based sensor for the simultaneous measurement of HR and pulse pressure [26]. The output is demodulated by fringe counting, and HR and pulse pressure information are obtained simultaneously through fringe pattern analysis and Kirchhoff–Love's plate theory, respectively. Y. Li et al. introduced an FFPI based on ethyl alpha-cyanoacrylate (EtCNA) for HR monitoring [27]. The FFPI is fixed in the capillary tube by using an EtCNA binder. Due to the low Young's modulus of EtCNA, the sensor can detect low-frequency vibration with high sensitivity.

2.5. The Comparison of Different Interferometers for Vital Signs Monitoring

Interferometry in optics is one of the most sensitive detection techniques known. The above four interferometers are sensors that use the phase change of light waves in the optical fiber caused by external factors to detect various parameters. Their comparison is shown in **Table 1**. Both MZI and MI are dual-beam interferometers with very similar structures. However, since MI needs to be coated on the fiber end face, it is slightly more difficult to manufacture than MZI. The two types of sensors require a sufficient length of optical fiber to make the sensing area large enough; therefore, the size is relatively large. They can be wrapped around the wrist or integrated into a cushion for vital signs monitoring. SI is very sensitive in detecting the rotation perpendicular to the loop plane, which is suitable for making gyroscopes. It has no obvious advantages in vital signs monitoring. The FFPI-based sensor is the most compact, suitable for pulse and body temperature measurement of the arm or wrist.

Table 1. The comparison of four interferometers for vital signs monitoring.

Interferometers	Manufacturing	Size	Cost	Feasibility
Mach–Zehnder interferometer	Easy	Large	Low	Feasible
Sagnac interferometer	Medium	Large	Low	Feasible
Michelson interferometer	Medium	Large	Low	Feasible
Fabry–Perot interferometers	Difficult	Small	High	Feasible

References

1. Zhang, F.; Yu, Y.; Zhong, J. Research status and development prospects of human vital signs monitoring clothing. IOP Conf. Ser. Earth Environ. Sci. 2019, 233, 042031.

2. Finocchiaro, G.; Sheikh, N.; Biagini, E.; Papadakis, M.; Sinagra, G.; Pelliccia, A.; Rapezzi, C.; Sharma, S.; Olivotto, I. The electrocardiogram in the diagnosis and management of patients with hypertrophic cardiomyopathy. Heart Rhythm 2020, 17, 142–151.

3. Liu, H.; Allen, J.; Zheng, D.; Chen, F. Recent development of respiratory rate measurement technologies. Physiol. Meas. 2019, 40, 07TR01.
4. Vinci, G.; Lindner, S.; Barbon, F.; Mann, S.; Hofmann, M.; Duda, A.; Weigel, R.; Koelpin, A. Six-port radar sensor for remote respiration rate and heartbeat vital-sign monitoring. IEEE Trans. Microw. Theory Tech. 2013, 61, 2093–2100.
5. Shao, D.; Tsow, F.; Liu, C.; Yang, Y.; Tao, N. Simultaneous monitoring of ballistocardiogram and photoplethysmogram using a camera. IEEE Trans. Biomed. Eng. 2016, 64, 1003–1010.
6. Hassan, M.A.; Malik, A.S.; Fofi, D.; Saad, N.M.; Ali, Y.S.; Meriaudeau, F. Video-based heartbeat rate measuring method using ballistocardiography. IEEE Sens. J. 2017, 17, 4544–4557.
7. Ramakrishnan, M.; Rajan, G.; Semenova, Y.; Farrell, G. Overview of Fiber Optic Sensor Technologies for Strain/Temperature Sensing Applications in Composite Materials. Sensors 2016, 16, 99.
8. Chen, Z.; Lau, D.; Teo, J.T.; Ng, S.H.; Yang, X.; Kei, P.L. Simultaneous measurement of breathing rate and heart rate using a microbend multimode fiber optic sensor. J. Biomed. Opt. 2014, 19, 057001.
9. Leal-Junior, A.G.; Diaz, C.R.; Leitão, C.; Pontes, M.J.; Marques, C.; Frizera, A. Polymer optical fiber-based sensor for simultaneous measurement of breath and heart rate under dynamic movements. Opt. Laser Technol. 2019, 109, 429–436.
10. Dziuda, Ł.; Krej, M.; Skibniewski, F.W. Fiber Bragg grating strain sensor incorporated to monitor patient vital signs during MRI. IEEE Sens. J. 2013, 13, 4986–4991.
11. Koyama, S.; Haseda, Y.; Ishizawa, H.; Okazaki, F.; Bonefacino, J.; Tam, H.-Y. Measurement of Pulsation Strain at the Fingertip Using a Plastic FBG Sensor. IEEE Sens. J. 2021, 21, 21537–21545.
12. Lyu, W.; Xu, W.; Yang, F.; Chen, S.; Tan, F.; Yu, C. Non-invasive measurement for cardiac variations using a fiber optic sensor. IEEE Photonics Technol. Lett. 2021, 33, 990–993.
13. Lyu, W.; Tan, F.; Chen, S.; Yu, C. Myocardial contractility assessment using fiber optic sensors. In Proceedings of the Asia Communications and Photonics Conference, Chengdu, China, 2–5 November 2019; p. M4A-152.
14. Lyu, W.; Chen, S.; Tan, F.; Yu, C. Non-invasive heart rate variability measurement during sleep based on fiber optic sensor. In Proceedings of the 2021 26th Optoelectronics and Communications Conference, Hong Kong, China, 3–7 July 2021; p. JS3F-2.
15. Tan, F.; Lyu, W.; Chen, S.; Liu, Z.; Yu, C. Contactless vital signs monitoring based on few-mode and multi-core fibers. Opto-Electron. Adv. 2020, 3, 190034.

16. Ke, C.; Cai, Y.; Zhao, T.; Li, Z. Research on intelligent mattress based on improved SMS structure sensing fiber. J. Phys. Conf. Ser. 2021, 1082, 022023.

17. Wang, R.; Zhao, J.; Sun, Y.; Yu, H.; Zhou, N.; Zhang, H.; Jia, D. Wearable respiration monitoring using an in-line few-mode fiber Mach-Zehnder interferometric sensor. Biomed. Opt. Express 2020, 11, 316–329.

18. Tan, F.; Chen, S.; Lyu, W.; Liu, Z.; Yu, C.; Lu, C.; Tam, H.Y. Non-invasive human vital signs monitoring based on twin-core optical fiber sensors. Biomed. Opt. Express 2019, 10, 5940–5951.

19. Chen, W.; Zhang, Y.; Yang, H.; Qiu, Y.; Li, H.; Chen, Z.; Yu, C. Non-invasive measurement of vital signs based on seven-core fiber interferometer. IEEE Sens. J. 2021, 21, 10703–10710.

20. Zhang, J.; He, Y.; Tan, F.; Chen, S.; Lyu, W.; Yang, F.; Yu, C. IJK complex detection within BCG signal based on multi-core fiber sensors. In Proceedings of the Asia Communications and Photonics Conference/International Conference on Information Photonics and Optical Communications 2020 (ACP/IPOC), Beijing, China, 24–27 October 2020; p. S3G-3.

21. Qu, J.; Shen, Y.; Xu, W.; Tan, F.; Yu, C.; Yu, C. Non-invasive vital signs monitoring based on polarization maintaining fiber and Sagnac interferometer. In Proceedings of the 24th OptoElectronics and Communications Conference/International Conference Photonics in Switching and Computing, OECC/PSC 2019, Fukuoka, Japan, 7–11 July 2019; p. 8817846.

22. Ke, C.; Cai, Y.; Zhao, T.; Li, Z. Research on Smart Mattress Based on Fiber Unbalanced Sagnac Loop. IOP Conf. Ser. Earth Environ. Sci. 2021, 769, 042039.

23. Zazula, D.; Đonlagić, D.; Šprager, S. Application of fibre-optic interferometry to detection of human vital signs. J. Laser Health Acad. 2012, 2012, 27–32.

24. Šprager, S.; Đonlagić, D.; Zazula, D. Heartbeat detection applying activity index on optical interferometric signal. In Proceedings of the 11th WSEAS international conference on Instrumentation, Measurement, Circuits and Systems, and Proceedings of the 12th WSEAS International Conference on Robotics, Control and Manufacturing Technology, and Proceedings of the 12th WSEAS International Conference on Multimedia Systems & Signal Processing, Rovaniemi, Finland, 18–20 April 2012; pp. 77–82.

25. Pullteap, S.; Samartkit, P. A High Sensitivity of Vital Signs Detector using Fiber Optic-based Fabry-Perot Interferometer. ECTI Trans. Electr. Eng. Electron. Commun. 2020, 18, 98–106.

26. Samartkit, P.; Pullteap, S.; Seat, H.C. Validation of Fiber Optic-Based Fabry–Perot Interferometer for Simultaneous Heart Rate and Pulse Pressure Measurements. IEEE Sens. J. 2020, 21, 6195–6201.

27. Li, Y.; Dong, B.; Chen, E.; Wang, X.; Zhao, Y. Heart-rate monitoring with an ethyl alpha-cyanoacrylate based fiber fabry-perot sensor. IEEE J. Sel. Top. Quantum Electron. 2020, 27, 1–6.