

For research article

Response to Reviewer 1 Comments

1. Summary

Dear Reviewer 1:

Gratefully thank you for the valuable comments. To each problem listed in the comments, we have given enough consideration and made some corrections, which are red underlined in revised manuscript. Please find the detailed responses below and the corresponding revisions in the re-submitted files.

2. Questions for General Evaluation	Reviewer's Evaluation	Response and Revisions
Does the introduction provide sufficient background and include all relevant references?	Can be improved	Please see the additional clarifications and revised manuscript below.
Are all the cited references relevant to the research?	Yes	No response
Is the research design appropriate?	Yes	No response
Are the methods adequately described?	Can be improved	Please see the revised manuscript below.
Are the results clearly presented?	Yes	No response
Are the conclusions supported by the results?	Yes	No response

3. Point-by-point response to Comments and Suggestions for Authors

Comments 1: *The authors of this manuscript did important work to measure the temperature of induction motors by FMF FBGs. I suggest the authors describe some necessary details in the abstract and conclusion sections, such as temperature range for measurement, accuracy obtained, speed/load of the motors and some on, and highlight its innovative value. The last sentence in the abstract is not appropriate, because the manuscript only solves the issue for temperature measurement, not the multiple physical fields. In addition, common FBGs with single mode fiber and weak reflection FBGs have been applied to the same or similar objects, so, the obvious or potential advantages of the FMF FBGs should be highlighted by some discussion or analysis in the introduction and conclusion.*

Response 1: (1) Thank you for your prudence and good suggestion. According to your suggestions, in the abstract and conclusion, we have added the more relevant details about this research such as accuracy obtained, motor speed/load, as well as the limitations of this

study and further research prospects.

The revised content of the abstract is as follows: As a proof of concept, the system demonstrates experiments in multiplexed temperature sensing for motor stators using the fundamental mode LP₀₁ and high-order spatial modes LP₁₁, LP₂₁, and LP₀₂. The FBG sensitivity carried by the LP₀₁, LP₁₁, LP₂₁, and LP₀₂ mode is 0.0107 nm/°C, 0.0106 nm/°C, 0.0097 nm/°C, and 0.0116 nm/°C, respectively. The dynamic temperature changes of the stator at different positions of the motor under different speeds of 1k rpm, 1.5k rpm, 2k rpm with no load, 3 kg load, and 5 kg load, as well as at three specific speed-load combinations of 1.5k rpm_3kg, 1k rpm_0kg, 2krpm_5kg and so on are measured respectively, and the measured results of different spatial modes are compared and analyzed. The findings indicate that different spatial modes can accurately reflect temperature variations at various positions in the motor stator winding.

The revised content of the conclusion is as follows: As a proof of concept, a mode division motor temperature FBG multiplexing system based on a photonic lantern is established, using the fundamental mode LP₀₁ and higher-order spatial modes LP₁₁, LP₂₁, and LP₀₂ as examples to conduct multiplexed experiments for multi-point temperature sensing of the motor stator. The study tests the dynamic temperature changes at different positions of the motor stator under various conditions for a three-phase induction motor at three different speeds of 1k rpm, 1.5k rpm, 2k rpm with no load, 3 kg load, and 5 kg load, as well as at three specific speed-load combinations of 1.5k rpm_3kg, 1k rpm_0kg, 2krpm_5kg, and another set of three speed-load conditions of 2k rpm_5kg, 250 rpm_0kg, 2k rpm_5kg. The measurement results of each spatial model are compared and analyzed. The experimental results indicate that the motor multiple-channel temperature optical sensing system based on the fundamental spatial mode LP₀₁ and higher-order spatial modes LP₁₁, LP₂₁, and LP₀₂ can achieve real-time synchronous monitoring of the working temperature changes at different parts of the motor stator winding. Among them, the jump abnormal data of LP₀₁ mode accounted for 1.6%, while jump abnormal data of the high-order modes LP₁₁, LP₂₁, and LP₀₂ accounted for 4.5%, 0.6%, and 0.8%, respectively. The reason for the higher rate of jump abnormal data in the LP₁₁ mode is that the testing area is on the internal copper wire winding with the insulation layer stripping, leading to a larger range of temperature changes and consequently more frequent jumps. In terms of fluctuations, while the fundamental mode LP₀₁ showed 5 instances of fluctuation, the high-order modes LP₁₁, LP₂₁, and LP₀₂ exhibited 8, 6, and 10 instances of fluctuations, respectively. The higher-order modes are more prone to fluctuations due to mode crosstalk in FMFs and photonic lanterns. In summary, the scheme can simultaneously detect the temperature change of different positions of the motor through various spatial modes, enhance the sensing capability of the sensor system, reduce the cost of the multiplexing system, and have high reusability and reliability. This scheme provides a novel approach for multiplexed sensing in monitoring multiple physical fields for motors. However, how to effectively eliminate the impact of mode crosstalk and improve the stability of measurements in high-order spatial modes still requires further in-depth research.

Please refer to the red sentences in the “Abstract” and “Conclusions” section of the revised

manuscript in pages 1 and 11, respectively.

(2) Thank you for your suggestion. We apologize for the unreasonable narration and have removed the last sentence in the abstract according to your recommendation

Please refer to the “Abstract” section of the revised manuscript in page 1.

(3) Thank you for your prudence and good suggestion. According to your suggestions, the obvious or potential advantages of the FMF FBGs has briefly analyzed by some discussion or analysis in the introduction and conclusion. Currently, for the common FBGs sensor system with single mode fiber, in order to achieve multipoint measurements, various multiplexing techniques have been proposed, such as Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM), Spatial Division Multiplexing (SDM), and hybrid multiplexing techniques. Among these technologies, the WDM allows for the multiplexing of multiple FBGs, each with a different central wavelength, on the same optical path. To prevent the overlap of adjacent FBG operating ranges, each FBG must occupy a unique wavelength range. The TDM employs a time-domain separation approach to distinguish the reflected spectra of FBGs, allowing the multiplexing of FBGs with identical or different central reflection wavelengths into the same sensing system. This approach is highly adaptable to various light sources. However, TDM cannot achieve synchronous detection with multiple sensors, which is crucial for precise fault localization. The SDM technology, by allocating multiple FBGs to different spatial optical paths, addresses the crosstalk issue that arises when multiple FBGs are serially connected on a single optical fiber, resulting in higher measurement accuracy. However, the SDM structure requires the use of optical switch devices to distribute transmission channels. The multiplexing capacity is limited by the optical switch devices. Additionally, the complexity and cost of the system are higher due to the necessity of these optical switching components. These factors present challenges in implementing SDM in practical, large-scale sensing applications.

The scheme proposed in this article utilizes the spatial mode dimension to allocate multiple FBGs to the optical paths carried by different spatial modes, achieving multiplexed sensing and multi-point temperature monitoring for the motor. Compared with traditional optical fiber sensing multiplexing systems, it can simultaneously detect the reflection spectrum change signals caused by temperature variations in each spatial mode, enhancing the sensing capacity of the sensor system and reducing the cost of the multiplexing system.

Please refer to the red sentences in the “Introduction” and “Conclusions” section of the revised manuscript in pages 2 and 11, respectively.

4. Response to Comments on the Quality of English Language

Point: *We tried our best to improve the quality of English Language and made some changes in the manuscript. These changes will not influence the content and framework of the paper.*

Response: (1) In the paragraph 2 of the page 2, “The paper exemplifies this with a motor temperature sensing multiplexing system using four spatial modes LP₀₁, LP₁₁, LP₂₁, and LP₀₂, and validates it experimentally.” has been modified to “The paper demonstrates this concept using a motor temperature sensing multiplexing system that employs four spatial modes LP₀₁,

LP₁₁, LP₂₁, and LP₀₂, and validates the system experimentally.”.

(2) In the paragraph 1 of the page 2, “Sitong Chen et al. introduces, Yihang Wu et al. investigate, Xueli Yang et al. fabricate, Matthias Fabian et al, develop, et al.” has been modified to “Sitong Chen et al. introduced, Yihang Wu et al. investigated, Xueli Yang et al. fabricated, Matthias Fabian et al, developed, et al.”

(3) In the abstract, “The paper establishes a photonics lantern-based mode division...” has been modified to “The paper establishes and demonstrates a photonics lantern-based....”.

(4) In the paragraph 1 of the page 4, “Measurements are taken for the wavelength variations in the center of the reflected spectra carried by the four spatial modes of FBG₁, FBG₂, FBG₃, and FBG₄, respectively.” has been modified to “The central wavelength variations of FBG₁, FBG₂, FBG₃ and FBG₄ carried by four spatial modes is measured, respectively.”.

(5) In addition, the problems misspelled words, wrong or missing prepositions, determiner use (a/an/the/this, etc.), conjunction use, confused words, incorrect verb forms, punctuation in compound/complex sentences, and mixed dialects of English and so on have been revised one by one.

There are also some other modifications, which are not listed here. For the specific modifications, please refer to red mark in the revised manuscript.

5. Additional clarifications

Point: Does the introduction provide sufficient background and include all relevant references?

Response: Thank you for your prudence and good suggestion. According to your suggestions, the related research reference has been expanded, and several references related to the methods for eliminating dead zone has been cited in the revised manuscript. Anees Mohammed et al. proposed an on-line internal temperature measurement scheme based on FBG sensing technology for monitoring the stator windings of low-voltage winding motors. The scheme, which targets the internal structure of the electric motor's stator windings, involves the design of an FBG temperature sensor encapsulated in a polyether ether ketone (PEEK) sheath to meet the requirements for internal thermal monitoring of the motor [1]. At the same time, the FBG sensors are used to monitor the temperature change of the motor, and the time domain and frequency domain analysis are carried out to realize the effective diagnosis of the severity of bearing faults [2]. The monitoring of the motor's temperature involves comprehensive measurements at multiple points, where the multiplexing method of fiber grating becomes crucial. To achieve multipoint high-precision measurements, various multiplexing techniques have been proposed, such as Wavelength Division Multiplexing (WDM) [3,4], Time Division Multiplexing (TDM) [5], Spatial Division Multiplexing (SDM) [6], and hybrid multiplexing techniques [7]. Among these technologies, the WDM allows for the multiplexing of multiple FBGs, each with a different central wavelength, on the same optical path. The TDM employs a time-domain separation approach to distinguish the reflected spectra of FBGs, allowing the multiplexing of FBGs with identical or different central reflection wavelengths into the same sensing system. This approach is highly adaptable to various light sources. The SDM technology, by allocating multiple FBGs to different spatial optical paths, addresses the crosstalk issue that arises when multiple FBGs are serially

connected on a single optical fiber, resulting in higher measurement accuracy. The above scheme provides a new idea for the comprehensive multi-point detection of motor temperature.

- [1] Anees Mohammed, and Siniša Djurović. Stator Winding Internal Thermal Monitoring and Analysis Using In Situ FBG Sensing Technology[J]. IEEE Transactions on Energy Conversion, 2018, 22(3): 1508-1518.
- [2] Anees Mohammed, and Siniša Djurović. Electric Machine Bearing Health Monitoring and Ball Fault Detection by Simultaneous Thermo-Mechanical Fibre Optic Sensing [J]. IEEE Transactions on Energy Conversion, 2021, 36 (1): 71-80.
- [3] Yibeltal Chanie Manie, Peng-Chun Peng, Run-Kai Shiu, Yuan-Ta Hsu, Ya-Yu Chen, Guan-Ming Shao, and Justin Chiu. Enhancement of the multiplexing capacity and measurement accuracy of FBG sensor system using IWDM technique and deep learning algorithm [J]. Journal of Lightwave Technology, 2020, 38(6): 1589-1603.
- [4] Xunzhou Xiao, Baijie Xu, Xizhen Xu, Bin Du, Ziyong Chen, Cailing Fu, Changrui Liao, Jun He, and Yiping Wang. Femtosecond laser auto-positioning direct writing of a multicore fiber Bragg grating array for shape sensing [J]. Optics Letters, 2022, 47(4): 758-761.
- [5] Fan Yang, Wenjia Zhang, Qingwen Liu, and Zuyuan He. Silicon-microring-based interrogator for TDM-FBG sensors enabled by pulse compression [J]. Optics Letters, 2020, 45(23): 6402-6405.
- [6] Sikdar D, Tiwari V, Soni A, Jaiswal R, and Bhanot S. Polarization multiplexed interrogation technique for FBG sensor array [J]. Photonic Sensors, 2015, 5 (3): 193-201.
- [7] Hwang D, Seo D-C, Kwon I-B and Chuang Y. Restoration of reflection spectra in a serial FBG sensor array of a WDM/TDM measurement system [J]. Sensors, 2012, 12(9): 12836-12843.

Please refer to the red sentences in the "Introduction" and "References" sections of the revised manuscript in page 2 and page 11, respectively.

At last, let us express our gratefulness to you for reviewing this manuscript again. We are looking forward to your further suggestions.

Best wishes to you

Yours truly

Feng Liu

Response to Reviewer 2 Comments

1. Summary

Dear Reviewer 2:

Gratefully thank you for the valuable comments. To each problem listed in the comments, we have given enough consideration and made some corrections, which are red underlined in revised manuscript. Please find the detailed responses below and the corresponding revisions in the re-submitted files.

2. Questions for General Evaluation	Reviewer's Evaluation	Response and Revisions
Does the introduction provide sufficient background and include all relevant references?	Must be improved	Please see the responses 1, 2, and revised manuscript below.
Are all the cited references relevant to the research?	Can be improved	Please see the response 2 and revised manuscript below.
Is the research design appropriate?	Can be improved	Please see the response 3 and revised manuscript below.
Are the methods adequately described?	Can be improved	Please see the response 3 and revised manuscript below.
Are the results clearly presented?	Can be improved	Please see the revised manuscript below.
Are the conclusions supported by the results?	Can be improved	Please see the responses 5 and revised manuscript below.

3. Point-by-point response to Comments and Suggestions for Authors

Comments 1: *In the abstract part, the author should add some background about this research in brief.*

Response 1: Thank you for your prudence and good suggestion. As you recommended, we have added background about this research in the abstract part. The specific contents are as follows: Induction motors are widely applied in motor drive systems. The effective temperature monitoring is one of the keys to ensure the reliability and optimal performance of the motors. Therefore, this paper introduces a multiplexed optical temperature sensing system for induction motors based on a few-mode fiber (FMF) spatial mode diversity.

Please refer to lines 8 to 10 of the red sentence in the "Abstract" section of the revised manuscript on page 1.

Comments 2: *Please provide more related research reference, in present form, the background is*

insufficient.

Response 2: Thank you for your prudence and good suggestion. According to your suggestions, the related research reference has been expanded, and several references related to the methods for eliminating dead zone has been cited in the revised manuscript. Anees Mohammed et al. proposed an on-line internal temperature measurement scheme based on FBG sensing technology for monitoring the stator windings of low-voltage winding motors. The scheme, which targets the internal structure of the electric motor's stator windings, involves the design of an FBG temperature sensor encapsulated in a polyether ether ketone (PEEK) sheath to meet the requirements for internal thermal monitoring of the motor [1]. At the same time, the FBG sensors are used to monitor the temperature change of the motor, and the time domain and frequency domain analysis are carried out to realize the effective diagnosis of the severity of bearing faults [2]. The monitoring of the motor's temperature involves comprehensive measurements at multiple points, where the multiplexing method of fiber grating becomes crucial. To achieve multipoint high-precision measurements, various multiplexing techniques have been proposed, such as Wavelength Division Multiplexing (WDM) [3,4], Time Division Multiplexing (TDM) [5], Spatial Division Multiplexing (SDM) [6], and hybrid multiplexing techniques [7]. Among these technologies, the WDM allows for the multiplexing of multiple FBGs, each with a different central wavelength, on the same optical path. The TDM employs a time-domain separation approach to distinguish the reflected spectra of FBGs, allowing the multiplexing of FBGs with identical or different central reflection wavelengths into the same sensing system. This approach is highly adaptable to various light sources. The SDM technology, by allocating multiple FBGs to different spatial optical paths, addresses the crosstalk issue that arises when multiple FBGs are serially connected on a single optical fiber, resulting in higher measurement accuracy. The above scheme provides a new idea for the comprehensive multi-point detection of motor temperature.

- [1] Anees Mohammed, and Siniša Djurović. Stator Winding Internal Thermal Monitoring and Analysis Using In Situ FBG Sensing Technology[J]. IEEE Transactions on Energy Conversion, 2018, 22(3): 1508-1518.
- [2] Anees Mohammed, and Siniša Djurović. Electric Machine Bearing Health Monitoring and Ball Fault Detection by Simultaneous Thermo-Mechanical Fibre Optic Sensing [J]. IEEE Transactions on Energy Conversion, 2021, 36 (1): 71-80.
- [3] Yibeltal Chanie Manie, Peng-Chun Peng, Run-Kai Shiu, Yuan-Ta Hsu, Ya-Yu Chen, Guan-Ming Shao, and Justin Chiu. Enhancement of the multiplexing capacity and measurement accuracy of FBG sensor system using IWDM technique and deep learning algorithm [J]. Journal of Lightwave Technology, 2020, 38(6): 1589-1603.
- [4] Xunzhou Xiao, Baijie Xu, Xizhen Xu, Bin Du, Ziyong Chen, Cailing Fu, Changrui Liao, Jun He, and Yiping Wang. Femtosecond laser auto-positioning direct writing of a multicore fiber Bragg grating array for shape sensing [J]. Optics Letters, 2022, 47(4): 758-761.
- [5] Fan Yang, Wenjia Zhang, Qingwen Liu, and Zuyuan He. Silicon-microring-based interrogator for TDM-FBG sensors enabled by pulse compression [J]. Optics Letters, 2020, 45(23): 6402-6405.

- [6] Sikdar D, Tiwari V, Soni A, Jaiswal R, and Bhanot S. Polarization multiplexed interrogation technique for FBG sensor array [J]. Photonic Sensors, 2015, 5 (3): 193-201.
- [7] Hwang D, Seo D-C, Kwon I-B and Chuang Y. Restoration of reflection spectra in a serial FBG sensor array of a WDM/TDM measurement system [J]. Sensors, 2012, 12(9): 12836-12843.

Please refer to the red sentences in the “Introduction” and “References” sections of the revised manuscript in page 2 and page 12, respectively.

Comments 3: *In part 2: this part is confusing and not clear about the experimental principle and setup, please describe the composition of the experimental system separately.*

Response 3: Thank you for your prudence and good suggestion. According to your suggestions, we have described the composition of the experimental system separately. The specific contents are as follows: As illustrated in Fig. 1, the system mainly consists of a wide spectrum light source, an FMF circulator, a mode-selective photonic lantern, an FBG array, a spectrum analyzer, and a measured motor. The specific work flow of the system is as follows: A broad-spectrum light source's single-mode pigtail is eccentrically fusion spliced with the pigtail of port 1 of the FMF circulator by 2 μm , effectively exciting the fundamental mode LP_{01} , as well as higher-order spatial modes LP_{11} , LP_{21} , and LP_{02} . Subsequently, the multi-path spatial modes are outputted through port 2 of the FMF circulator, entering the photonic lantern for spatial mode transformation. They are converted to the corresponding fundamental mode LP_{01} , entering the FBG topological array. Under varying motor speeds and loads, the temperature changes cause alterations in the reflected spectra of the FBG sensors carried by different spatial modes. In this setup, the reflected spectra from the FBG topological array are directed back to a photonic lantern, which converts them into corresponding high-order spatial modes for multiplexing. The multiplexed spatial modes are then channeled through Port 2 into an FMF circulator, with the output from Port 3 entering a spectrometer for spectral detection and acquisition. Finally, the central wavelength of FBG is determined by finding the highest intensity point (wave peak) in the FBG reflection spectrum carried by LP_{01} , LP_{11} , LP_{21} , and LP_{02} modes through the central wavelength positioning. Then, according to the FBG linear fitting expression carried by each mode, the corresponding temperature change value of each point of the motor is calculated, and the multi-point synchronous detection of the motor temperature is realized.

Please refer to the red sentences in the “Experimental Principle and Setup” sections of the revised manuscript in page 3.

Comments 4: *In Fig.2 : What's the evidence of mathematical expressions and corresponding fitting results, especially about the fit coefficient, please give more reference.*

Response 4: Thank you for your prudence and good suggestion. According to your suggestions, we illustrate the mathematical expression and the corresponding fitting results in Fig.2, and the related research reference related to mathematical expressions and fit coefficient has been cited in the revised manuscript. The wavelength of FBG sensor is related to temperature change, and its basic mathematical relationship can be expressed as [1,2]:

$$\Delta\lambda_B = \lambda_B (\alpha + \xi) \Delta T \quad (1)$$

where $\Delta\lambda_B$ is the change of FBG wavelength, λ_B is the initial FBG wavelength, ΔT is the change in temperature, α is the thermal expansion coefficient of optical fiber, ξ is the thermo-optical coefficient of the fiber. It can be seen from Eq.(1) that λ_B , α and ξ are inherent properties of FBG, and when the temperature ΔT changes, the change of FBG's reflected wavelength is $\Delta\lambda_B$. According to this principle, the temperature variation range in the experiment is 20°C~100°C, and each temperature change of 20°C is taken as a data point to measure the change of the central wavelength of the reflection spectrum carried by four spatial modes. The least square curve fitting is performed on the experimental data. The relationship between FBG wavelength and temperature is obtained. The slope of the fitting curve represents the sensitivity of the sensor to temperature change, and the FBG sensitivity carried by the LP₀₁, LP₁₁, LP₂₁, and LP₀₂ mode is 0.0107 nm/°C, 0.0106 nm/°C, 0.0097 nm/°C, and 0.0116 nm/°C, respectively.

- [1] Anees Mohammed, and Siniša Djurović. Stator Winding Internal Thermal Monitoring and Analysis Using In Situ FBG Sensing Technology[J]. IEEE Transactions on Energy Conversion, 2018, 22(3): 1508-1518.
- [2] Kleiton de Moraes Sousa, Angelo A. Hafner, Hypolito José Kalinowski, and Jean Carlos Cardozo da Silva Determination of Temperature Dynamics and Mechanical and Stator Losses Relationships in a Three-Phase Induction Motor Using Fiber Bragg Grating Sensors [J]. IEEE Sensors Journal, 2012, 12(10): 3054-3061.

Please refer to the red sentences in the "Experiment Results and Analysis" and "References" sections of the revised manuscript in page 4 and page 12, respectively.

Comments 5: *The conclusions are weak, please give more information about this research, including the imitations and further research.*

Response 5: Thank you for your prudence and good suggestion. According to your suggestions, in the conclusion, we have added the more relevant details about this research such as accuracy obtained, motor speed/load, as well as the limitations of this study and further research prospects. The specific contents are as follows: As a proof of concept, a mode division motor temperature FBG multiplexing system based on a photonic lantern is established, using the fundamental mode LP₀₁ and higher-order spatial modes LP₁₁, LP₂₁, and LP₀₂ as examples to conduct multiplexed experiments for multi-point temperature sensing of the motor stator. The study teste the dynamic temperature changes at different positions of the motor stator under various conditions for a three-phase induction motor at three different speeds of 1k rpm, 1.5k rpm, 2k rpm with no load, 3 kg load, and 5 kg load, as well as at three specific speed-load combinations of 1.5k rpm_3kg, 1k rpm_0kg, 2k rpm_5kg, and another set of three speed-load conditions of 2k rpm_5kg, 250 rpm_0kg, 2k rpm_5kg. The measurement results of each spatial model are compared and

analyzed. The experimental results indicate that the motor multiple-channel temperature optical sensing system based on the fundamental spatial mode LP₀₁ and higher-order spatial modes LP₁₁, LP₂₁, and LP₀₂ can achieve real-time synchronous monitoring of the working temperature changes at different parts of the motor stator winding. Among them, the jump abnormal data of LP₀₁ mode accounted for 1.6%, while jump abnormal data of the high-order modes LP₁₁, LP₂₁, and LP₀₂ accounted for 4.5%, 0.6%, and 0.8%, respectively. The reason for the higher rate of jump abnormal data in the LP₁₁ mode is that the testing area is on the internal copper wire winding with the insulation layer stripping, leading to a larger range of temperature changes and consequently more frequent jumps. In terms of fluctuations, while the fundamental mode LP₀₁ showed 5 instances of fluctuation, the high-order modes LP₁₁, LP₂₁, and LP₀₂ exhibited 8, 6, and 10 instances of fluctuations, respectively. The higher-order modes are more prone to fluctuations due to mode crosstalk in FMs and photonic lanterns. In summary, the scheme can simultaneously detect the temperature change of different positions of the motor through various spatial modes, enhance the sensing capability of the sensor system, reduce the cost of the multiplexing system, and have high reusability and reliability. This scheme provides a novel approach for multiplexed sensing in monitoring multiple physical fields for motors. However, how to effectively eliminate the impact of mode crosstalk and improve the stability of measurements in high-order spatial modes still requires further in-depth research.

Please refer to the red sentences in the "Conclusions" section of the revised manuscript in page 11.

4. Response to Comments on the Quality of English Language

Point: *We tried our best to improve the quality of English Language and made some changes in the manuscript. These changes will not influence the content and framework of the paper.*

Response: (1) In the paragraph 2 of the page 2, "The paper exemplifies this with a motor temperature sensing multiplexing system using four spatial modes LP₀₁, LP₁₁, LP₂₁, and LP₀₂, and validates it experimentally." has been modified to "The paper demonstrates this concept using a motor temperature sensing multiplexing system that employs four spatial modes LP₀₁, LP₁₁, LP₂₁, and LP₀₂, and validates the system experimentally."

(2) In the paragraph 1 of the page 2, "Sitong Chen et al. introduces, Yihang Wu et al. investigate, Xueli Yang et al. fabricate, Matthias Fabian et al, develop, et al." has been modified to "Sitong Chen et al. introduced, Yihang Wu et al. investigated, Xueli Yang et al. fabricated, Matthias Fabian et al, developed, et al."

(3) In the abstract, "The paper establishes a photonics lantern-based mode division..." has been modified to "The paper establishes and demonstrates a photonics lantern-based....".

(4) In the paragraph 1 of the page 4, "Measurements are taken for the wavelength variations in the center of the reflected spectra carried by the four spatial modes of FBG₁, FBG₂, FBG₃, and FBG₄, respectively." has been modified to "The central wavelength variations of FBG₁, FBG₂, FBG₃ and FBG₄ carried by four spatial modes is measured, respectively."

(5) In addition, the problems misspelled words, wrong or missing prepositions, determiner use (a/an/the/this, etc.), conjunction use, confused words, incorrect verb forms, punctuation in compound/complex sentences, and mixed dialects of English and so on have been revised

one by one.

At last, let us express our gratefulness to you for reviewing this manuscript again. We are looking forward to your further suggestions.

Best wishes to you

Yours truly

Feng Liu

Response to Reviewer 3 Comments

1. Summary

Dear Reviewer 3:

Gratefully thank you for the valuable comments. To each problem listed in the comments, we have given enough consideration and made some corrections, which are red underlined in revised manuscript. Please find the detailed responses below and the corresponding revisions in the re-submitted files.

2. Questions for General Evaluation	Reviewer's Evaluation	Response and Revisions
Does the introduction provide sufficient background and include all relevant references?	Yes	No response
Are all the cited references relevant to the research?	Can be improved	Please see the Additional clarifications and revised manuscript below.
Is the research design appropriate?	Can be improved	Please see the responses 1-3 and revised manuscript below.
Are the methods adequately described?	Can be improved	Please see the responses 2 and revised manuscript below.
Are the results clearly presented?	Can be improved	Please see the responses 6, 7 and revised manuscript below.
Are the conclusions supported by the results?	Can be improved	Please see the responses 8 and revised manuscript below.

3. Point-by-point response to Comments and Suggestions for Authors

Comments 1: - *in the introduction there's the sentence "This serial topology has 80 comparatively lower reliability. In instances where a single FBG unit is damaged, it can 81 lead to a network failure in the subsequent system, thus reducing the reliability of the 82 multiplexed sensing system [17,18]." But in the proposed technology I don't see something that overcomes this limit. The kind of network proposed in figure 1 can be employed also for normal FBG sensors with DWDM-based interrogation system.*

Response 1: Thank you for pointing this out. As shown in Fig.1, the principle diagram of FBG sensing multiplexing method based on mode diversity is shown. By using the spatial mode dimension of FMF, multiple FBG channels are allocated to the optical paths carried by

different LP spatial modes to realize parallel multiplexing of multiple FBG sensors. When a single FBG unit is damaged, FBG carried by other spatial modes can continue to work, which solves the problem that the reliability of traditional WDM serial topology is relatively low. As you said, the kind of network proposed can be employed also for normal FBG sensors with DWDM-based interrogation system, as shown in Fig. 2. Each spatial mode is equivalent to the WDM serial multiplexing structure. When an FBG in one spatial mode is damaged, the network after it will crash. However, other path space patterns based on MDM and WDM can continue to be used to ensure system reliability. According to your suggestions, we have made a brief explanation of the above content in the revised manuscript.

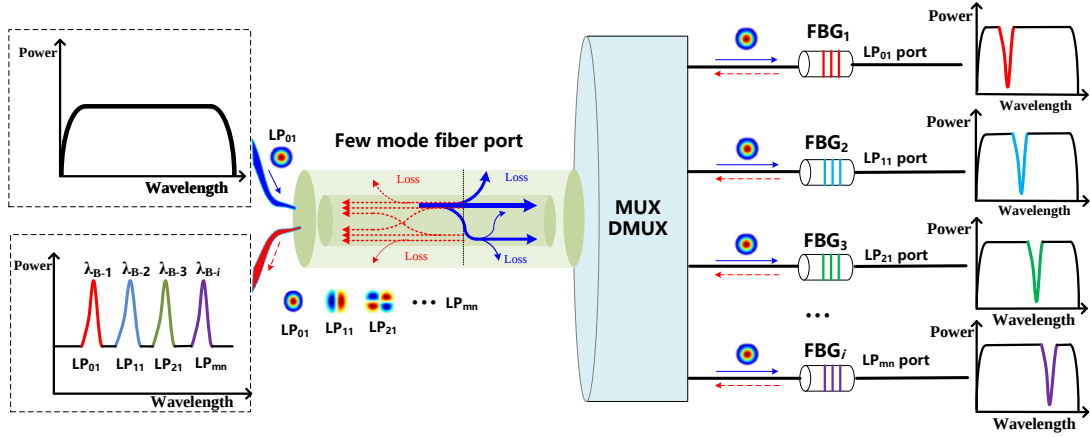


Fig. 1. Schematic diagram of FBG sensing multiplexing based on spatial mode diversity.

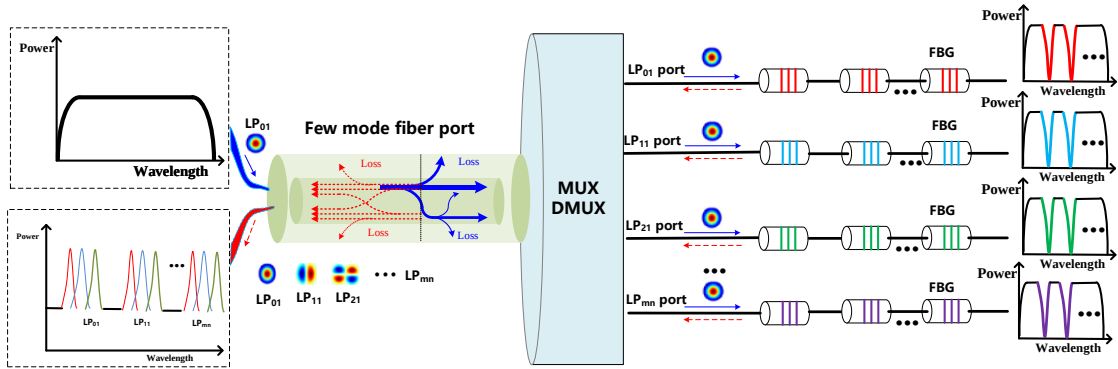


Fig. 2. Schematic diagram of FBG sensing multiplexing based on MDM and WDM.

Please refer to the red sentences in the “Experimental Principle and Setup” sections of the revised manuscript in page 4.

Comments 2: - the theoretical part in section 2 explaining the different FBG spatial mode is not clear at all. I don't understand if we are still talking about FBG structure playing with different mode to demodulate the signal, or if we are talking about different structure compared with FBG sensors.

Response 2: Thank you for your prudence and good suggestion. Firstly, according to your suggestion, in order to make the theoretical descriptions of different FBG spatial mode clearer in Section 2. We have described the composition of the experimental system separately. The specific contents are as follows: the system mainly consists of a wide spectrum light source, an FMF circulator, a mode-selective photonic lantern, an FBG array, a spectrum analyzer, and a measured motor. The specific work flow of the system is as follows: A broad-spectrum light

source's single-mode pigtail is eccentrically fusion spliced with the pigtail of port 1 of the FMF circulator by 2 μm , effectively exciting the fundamental mode LP_{01} , as well as higher-order spatial modes LP_{11} , LP_{21} , and LP_{02} . Subsequently, the multi-path spatial modes are outputted through port 2 of the FMF circulator, entering the photonic lantern for spatial mode transformation. They are converted to the corresponding fundamental mode LP_{01} , entering the FBG topological array. Under varying motor speeds and loads, the temperature changes cause alterations in the reflected spectra of the FBG sensors carried by different spatial modes. In this setup, the reflected spectra from the FBG topological array are directed back to a photonic lantern, which converts them into corresponding high-order spatial modes for multiplexing. The multiplexed spatial modes are then channeled through Port 2 into an FMF circulator, with the output from Port 3 entering a spectrometer for spectral detection and acquisition. Finally, the central wavelength of FBG is determined by finding the highest intensity point (wave peak) in the FBG reflection spectrum carried by LP_{01} , LP_{11} , LP_{21} , and LP_{02} modes through the central wavelength positioning. Then, according to the FBG linear fitting expression carried by each mode, the corresponding temperature change value of each point of the motor is calculated, and the multi-point synchronous detection of the motor temperature is realized.

Secondly, the content of this section is mainly to explain the principle, composition and implementation process of FBG multiplexing system based on mode diversity. As shown in Fig. 1, this method utilizes the spatial mode dimension of FMF, and multiple FBG channels are allocated to the optical paths carried by different LP spatial modes to realize parallel multiplexing of multiple FBG sensors. As you said, we achieve temperature measurement by demodulating the spectral changes of FBG carried by different spatial modes. Then the multi-point synchronous detection of motor temperature is realized.

Please refer to the red sentences in the "Experimental Principle and Setup" sections of the revised manuscript in pages 3 and 4.

Comments 3: - *I don't get if the device "photonic lantern" is designed by the authors or if is something got from the market. Again, which is the difference with a simple 4-channel wavelength demultiplexer interrogating 4 FBG array (compared for this case)?*

Response 3: Thank you for your prudence and good suggestion. The photonics lantern is already on the market. The photonic lantern we use is manufactured by Phoenix and its model number is 6-PLS-GI-15-1-2-2-MS. The photonic lantern focus on the conversion and multiplexing of spatial modes, capable of converting and multiplexing multiple LP_{01} modes into an FMF, while also being able to convert different spatial modes to the LP_{01} mode. In this paper, by utilizing FBGs carried by LP_{01} , LP_{11} , LP_{21} , and LP_{02} modes, multi-channel parallel temperature sensing is achieved, as shown in Fig. 3. On the other hand, wavelength-division multiplexers (WDMs) focus on the multiplexing of wavelengths. By using a combiner to synthesize light signals of different wavelengths into a single beam, they are transmitted through the fiber in the LP_{01} mode. At the receiving end, a demultiplexer is used to separate the signals of different wavelengths. The WDM allows for the multiplexing of multiple FBGs, each with a different central wavelength, on the same optical path, as shown in Fig. 4. Therefore, there is a significant difference between the two methods.

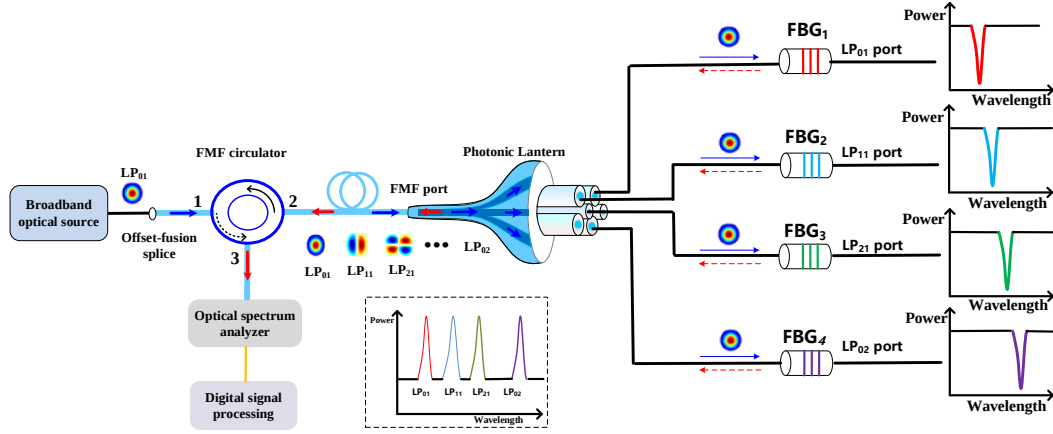


Fig.3. FBG multiplexing based on spatial mode diversity.

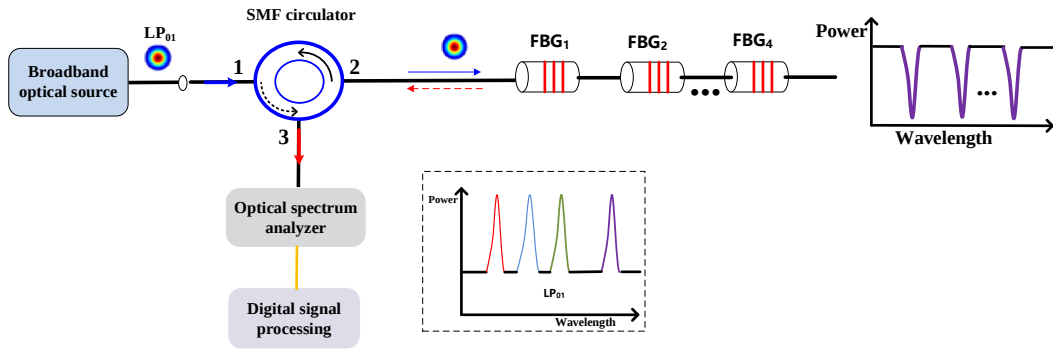


Fig.4. FBG multiplexing based on wavelength division multiplexing.

Comments 4: - *please spend more words regarding the interrogation performed, referred to figure 1. The signal was acquired with an OSA and processed digitally. Which is the proposed interrogation algorithm?*

Response 4: Thank you for your prudence and good suggestion. According to your suggestion, we have added some words regarding the interrogation performed. The central wavelength of FBG is determined by finding the highest intensity point (wave peak) in the FBG reflection spectrum carried by LP_{01} , LP_{11} , LP_{21} , and LP_{02} modes through the central wavelength positioning algorithm. Then, according to the FBG linear fitting expression carried by each mode, the corresponding temperature change value of each point of the motor is calculated, and the multi-point synchronous detection of the motor temperature is realized.

Please refer to the red sentences in the “Experimental Principle and Setup” sections of the revised manuscript in page 3.

Comments 5: - *As it is well known from the state-of-art, interrogation with OSA shows many limit to the FBG sensor interrogation. Authors should provide information to enhance the advantages of the proposed technology with the state-of-art (resolution, accuracy, speed, etc.).*

Response 5: Thank you for your prudence and good suggestion. As you said, interrogation with OSA shows many limit to the FBG sensor interrogation, such as such as resolution limit, dynamic range limit, scanning speed limit, multi-modal resolution, etc. In this paper, a new

multiplexing scheme based on spatial mode diversity is proposed mainly for FBG sensing multiplexing. By introducing the spatial mode dimension of low-mode fiber, FBG is allocated to multiple optical paths carried by different spatial modes, and the reflection spectrum of FBG in each spatial mode is multiplexed and detected. Emphasis is placed on the feasibility of novel reuse structures. At the same time, because the OSA used can meet the experimental requirements, the limiting factors of OSA are not analyzed in depth. Later, we will conduct in-depth research on the resolution, accuracy and speed of the new multiplexing system according to your suggestions, and further improve the mode diversity FBG multiplexing system for in-depth research.

Comments 6: - in Figure 2 the sensor calibration in temperature is shown. Usually, for this wide temperature range a cubic fit is employed. Please show the fit related data and compare (and comment) the result with a cubic fit.

Response 6: Thank you for your prudence and good suggestion. According to your suggestion, we have performed a cubic fit on the data, and linear fit and the cubic fit results are shown in Figs. 3(a) and 3(b), respectively. Through comparative analysis, it can be seen that the fitting degree R^2 of linear fitting is basically the same as that of cubic fitting. Because the linear fitting calculation is relatively simple, it is more convenient to accurately convert the measured reflected wavelength shift into temperature. We give a brief explanation of this content in the revised manuscript.

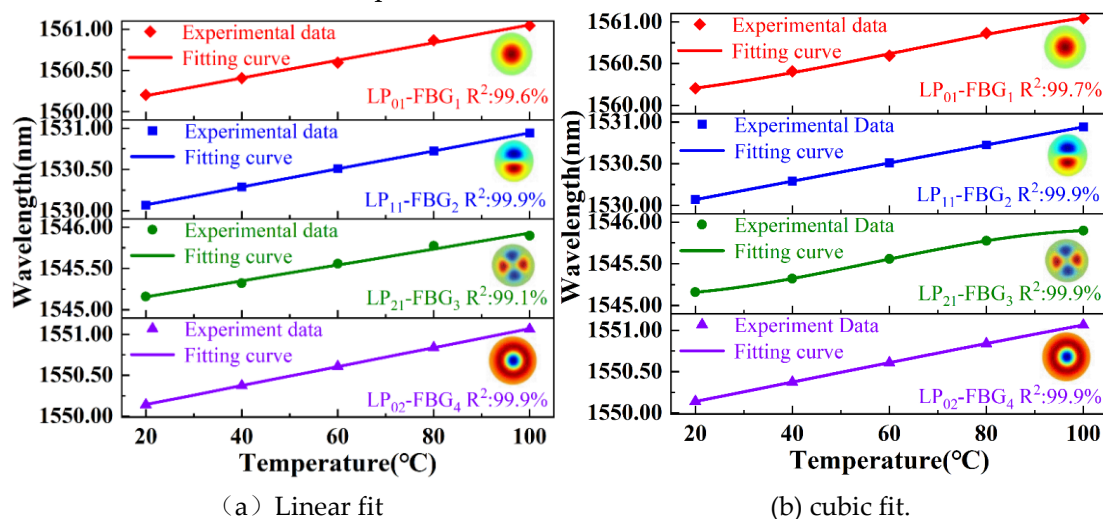


Fig.3. FBG Sensor calibration test data.

Please refer to red sentences and Fig.2 in the "Experiment Results and Analysis" sections of the revised manuscript in pages 4 and 5.

Comments 7: - please improve figure 5 with a legend explaining the difference between full and dotted line. Here I don't understand if the full line are curve fitting. If so, please provide fit data.

Response 7: Thank you for your prudence and good suggestion. We apologize for the unclear presentation of the data in the Fig.5 of the manuscript. The solid line in the figure is the fitting data, and the dashed line is the experimental measurement data. According to your suggestion, we have modified the legend in the figure, and the modified result is shown in Fig. 4 below.

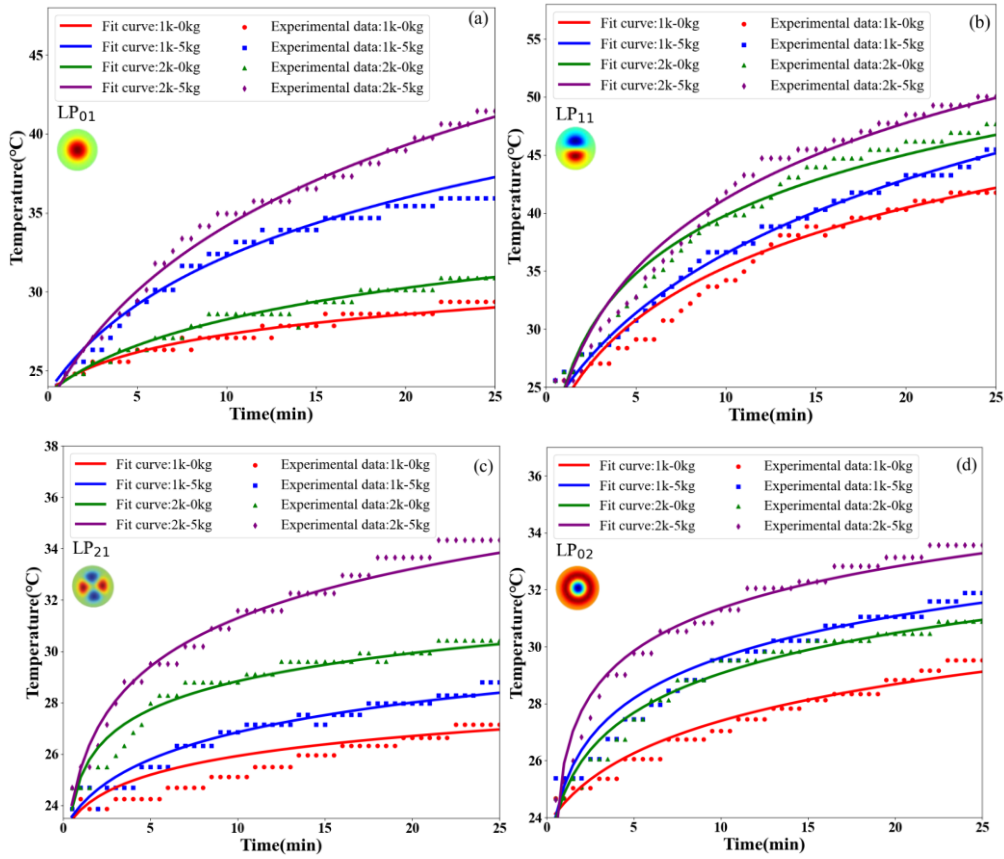


Fig.4. FBG temperature variation process carried by different spatial modes under different load operation conditions. (a) LP₀₁ mode, (b) LP₁₁ mode, (c) LP₂₁ mode, (d) LP₀₂ mode.

Please refer to the Fig.5 in the revised manuscript.

Comments 8: - *please improve conclusions with a deeper explanation of what was done.*

Response 8: Thank you for your prudence and good suggestion. According to your suggestions, in the conclusion, we have added the more relevant details about this research such as accuracy obtained, motor speed/load, as well as the limitations of this study and further research prospects. The specific contents are as follows: As a proof of concept, a mode division motor temperature FBG multiplexing system based on a photonic lantern is established, using the fundamental mode LP₀₁ and higher-order spatial modes LP₁₁, LP₂₁, and LP₀₂ as examples to conduct multiplexed experiments for multi-point temperature sensing of the motor stator. The study tests the dynamic temperature changes at different positions of the motor stator under various conditions for a three-phase induction motor at three different speeds of 1k rpm, 1.5k rpm, 2k rpm with no load, 3 kg load, and 5 kg load, as well as at three specific speed-load combinations of 1.5k rpm_3kg, 1k rpm_0kg, 2krpm_5kg, and another set of three speed-load conditions of 2k rpm_5kg, 250 rpm_0kg, 2k rpm_5kg. The measurement results of each spatial model are compared and analyzed. The experimental results indicate that the motor multiple-channel temperature optical sensing system based on the fundamental spatial mode LP₀₁ and higher-order spatial modes LP₁₁, LP₂₁, and LP₀₂ can achieve real-time synchronous monitoring of the working temperature changes at different parts of the motor stator winding. Among them, the jump abnormal data of LP₀₁ mode accounted for 1.6%, while

jump abnormal data of the high-order modes LP₁₁, LP₂₁, and LP₀₂ accounted for 4.5%, 0.6%, and 0.8%, respectively. The reason for the higher rate of jump abnormal data in the LP₁₁ mode is that the testing area is on the internal copper wire winding with the insulation layer stripping, leading to a larger range of temperature changes and consequently more frequent jumps. In terms of fluctuations, while the fundamental mode LP₀₁ showed 5 instances of fluctuation, the high-order modes LP₁₁, LP₂₁, and LP₀₂ exhibited 8, 6, and 10 instances of fluctuations, respectively. The higher-order modes are more prone to fluctuations due to mode crosstalk in FMFs and photonic lanterns. In summary, the scheme can simultaneously detect the temperature change of different positions of the motor through various spatial modes, enhance the sensing capability of the sensor system, reduce the cost of the multiplexing system, and have high reusability and reliability. This scheme provides a novel approach for multiplexed sensing in monitoring multiple physical fields for motors. However, how to effectively eliminate the impact of mode crosstalk and improve the stability of measurements in high-order spatial modes still requires further in-depth research.

Please refer to the red sentences in the “Conclusions” section of the revised manuscript in page 11.

4. Additional clarifications

Point: *Are all the cited references relevant to the research? Can be improved.*

Response: Thank you for your prudence and good suggestion. According to your suggestions, the related research reference has been expanded, and several references related to the methods for eliminating dead zone has been cited in the revised manuscript. Anees Mohammed et al. proposed an on-line internal temperature measurement scheme based on FBG sensing technology for monitoring the stator windings of low-voltage winding motors. The scheme, which targets the internal structure of the electric motor's stator windings, involves the design of an FBG temperature sensor encapsulated in a polyether ether ketone (PEEK) sheath to meet the requirements for internal thermal monitoring of the motor [1]. At the same time, the FBG sensors are used to monitor the temperature change of the motor, and the time domain and frequency domain analysis are carried out to realize the effective diagnosis of the severity of bearing faults [2]. The monitoring of the motor's temperature involves comprehensive measurements at multiple points, where the multiplexing method of fiber grating becomes crucial. To achieve multipoint high-precision measurements, various multiplexing techniques have been proposed, such as Wavelength Division Multiplexing (WDM) [3,4], Time Division Multiplexing (TDM) [5], Spatial Division Multiplexing (SDM) [6], and hybrid multiplexing techniques [7]. Among these technologies, the WDM allows for the multiplexing of multiple FBGs, each with a different central wavelength, on the same optical path. The TDM employs a time-domain separation approach to distinguish the reflected spectra of FBGs, allowing the multiplexing of FBGs with identical or different central reflection wavelengths into the same sensing system. This approach is highly adaptable to various light sources. The SDM technology, by allocating multiple FBGs to different spatial optical paths, addresses the crosstalk issue that arises when multiple FBGs are serially connected on a single optical fiber, resulting in higher measurement accuracy. The above scheme provides a new idea for the comprehensive multi-point detection of motor

temperature.

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- [7] Hwang D, Seo D-C, Kwon I-B and Chuang Y. Restoration of reflection spectra in a serial FBG sensor array of a WDM/TDM measurement system [J]. Sensors, 2012, 12(9): 12836-12843.

Please refer to the red sentences in the "Introduction" and "References" sections of the revised manuscript in page 2 and page 11, respectively.

At last, let us express our gratefulness to you for reviewing this manuscript again. We are looking forward to your further suggestions.

Best wishes to you

Yours truly

Feng Liu

A Multiplexing Optical Temperature Sensing System for induction motors Using Few-mode Fiber Spatial Mode Diversity

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Abstract: Induction motors are widely applied in motor drive systems. The effective temperature monitoring is one of the keys to ensure the reliability and optimal performance of the motors. Therefore, this paper introduces a multiplexed optical temperature sensing system for induction motors based on a few-mode fiber (FMF) spatial mode diversity. By using the spatial mode dimension of FMF, fiber Bragg grating (FBG) carried by different spatial modes of optical paths are embedded in different positions of the motor to realize multi-point synchronous multiplexing temperature monitoring. The paper establishes and demonstrates a photonics lantern-based mode division sensing system for motor temperature monitoring. As a proof of concept, the system demonstrates experiments in multiplexed temperature sensing for motor stators using the fundamental mode LP₀₁ and high-order spatial modes LP₁₁, LP₂₁, and LP₀₂. The FBG sensitivity carried by the above mode is 0.0107 nm/°C, 0.0106 nm/°C, 0.0097 nm/°C, and 0.0116 nm/°C, respectively. The dynamic temperature changes of the stator at different positions of the motor under different speeds of 1k rpm, 1.5k rpm, 2k rpm with no load, 3 kg load, and 5 kg load, as well as at three specific speed-load combinations of 1.5k rpm_3kg, 1k rpm_0kg, 2krpm_5kg and so on are measured respectively, and the measured results of different spatial modes are compared and analyzed. The findings indicate that different spatial modes can accurately reflect temperature variations at various positions in the motor stator winding.

Keywords: motor temperature monitoring; few mode fiber; spatial mode division; fiber Bragg grating

1. Introduction

With the advancement of high-speed motors, the temperature of motor rotors and stators has become a crucial metric in the design and health monitoring of motors. Effective temperature monitoring is key to ensuring the reliability and optimal performance of these motors. Given that the losses incurred due to motor failures can potentially exceed the cost of the motor itself, the significance of predictive maintenance for motors is substantial [1–3]. Currently, motor temperature monitoring is primarily categorized into two methods: average temperature monitoring and local temperature monitoring. The former mainly includes the resistance method [4] and infrared thermometry [5], while local temperature monitoring primarily involves the embedding of electronic temperature sensors [6, 7] and fiber Bragg grating (FBG) temperature sensors [8–11]. The resistance method, widely used at present, is capable of estimating the average temperature of the entire rotor winding. However, this average temperature measurement sometimes fails to detect the emergence of local hot spots, and its measurement accuracy is relatively low. Infrared thermometry can obtain the average temperature along its scanning circumference, offering higher accuracy and resolution. Nevertheless, the difficulty in positioning the temperature probe deep into the narrow air gaps of generators limits the application of infrared

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Last-name

Received: date

Revised: date

Accepted: date

Published: date



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thermometry. The primary approach for monitoring local hot spots involves embedding temperature sensors at specific locations. Owing to the relatively large size and mass of electronic thermocouples, thermal resistors, or semiconductor temperature sensors, they are not suitable for use in compact motors. Moreover, the sensitivity of these electronic sensors to high voltage and electromagnetic interference affects the accuracy of the signal acquisition.

In comparison, optical measurement techniques have the advantage of being immune to electromagnetic interference. The FBG sensors are characterized by their small size and **lightweight**, allowing them to be easily integrated within the motor. These sensors enable quasi-distributed measurement and have minimal impact on the operational performance of the motor. Therefore, employing FBG sensors for monitoring the temperature of motors presents an effective solution, as demonstrated by the following examples: Anees Mohammed et al. proposed an on-line internal temperature measurement scheme based on FBG sensing technology for monitoring the stator windings of low-voltage winding motors. The scheme, which targets the internal structure of the electric motor's stator windings, involves the design of an FBG temperature sensor encapsulated in a polyether ether ketone (PEEK) sheath to meet the requirements for internal thermal monitoring of the motor [3]. At the same time, the FBG sensors are used to monitor the temperature change of the motor, and the time domain and frequency domain analysis are carried out to realize the effective diagnosis of the severity of bearing faults [10]. Sitong Chen et al. introduced a temperature monitoring system based on the FBG for the generator or electric motor rotor. With a resolution of 0.1°C , the system can be able to achieve an error of 0.5°C over a range of $30\text{--}180^{\circ}\text{C}$ [11]. Anees Mohammed et al. propose a random wound stator winding thermal monitoring scheme for permanent magnet synchronous motors utilizing an end-winding embedded, ring shaped, FBG thermal sensing array [12]. Marcelo Martins Werneck et al. employed an FBG wavelength division multiplexing (WDM) system to monitor the stator temperature variations of a 216 MW hydroelectric generator operating at full load at 95°C . The sensor used in this study had a temperature response range of $20\text{--}85^{\circ}\text{C}$, with an average sensitivity of approximately $13\text{ pm}/^{\circ}\text{C}$ [13]. Additionally, Yihang Wu et al. investigated a scheme that involved the application of a single nickel-plated FBG sensor head in the end windings of an induction motor, enabling the simultaneous sensing of relative flux and absolute temperature [14]. Xueli Yang et al. fabricated a FBG temperature sensor with rapid response and excellent antivibration performance, which was applied to the temperature monitoring of small size motor for a hydraulic pump and achieved ideal results [15]. While utilizing FBG for measuring the temperature of motor rotors, some researchers have dedicated their efforts to multi-physical field monitoring. For instance, D. Hidn et al. use FBG to measure the temperatures of the stator and rotor of a 2 kW permanent magnet motor. This study also monitored the vibration of the motor's stator casing and the torque of its shaft, thus confirming the feasibility of using FBG for multi-parameter monitoring of motors [16]. Furthermore, Matthias Fabian et al. developed a comprehensive motors state monitoring system incorporating multiple parameters and sensors. This system is capable of detecting the temperatures of rotor bearings, rotor windings, and stator windings, as well as measuring parameters such as the torque and speed of rotor bearings and the displacement of stator teeth [17]. Based on the aforementioned analysis, it is evident that motor temperature measurements using FBG technology have achieved significant improvements in terms of measurement range and temperature detection sensitivity. The monitoring of the motor's temperature involves comprehensive measurements at multiple points, where the multiplexing method of fiber grating becomes crucial. Currently, for the common FBGs sensor system with single mode fiber, in order to achieve multipoint measurements, to achieve multipoint high-precision measurements, various multiplexing techniques have been proposed, such as Wavelength Division Multiplexing (WDM) [18], Time Division Multiplexing (TDM) [19], Spatial Division Multiplexing (SDM) [20], and hybrid multiplexing techniques [21]. The

above scheme provides a new idea for the comprehensive multi-point detection of motor temperature.

This paper proposes a novel FBG multiplexed parallel topology based on the spatial mode diversity of FMF for quasi-distributed, multi-point, synchronous, real-time temperature monitoring of motors. Utilizing the unique spatial mode dimensions of FMF [22,23], FBGs carried by different spatial mode pathways are embedded in various locations of the motor to simultaneously monitor temperatures in different areas of the stator windings. The paper demonstrates this concept using a motor temperature sensing multiplexing system that employs four spatial modes LP₀₁, LP₁₁, LP₂₁, and LP₀₂, and validates the system experimentally. The results indicate that the proposed FBG sensor multiplexing system, based on spatial mode diversity, effectively achieves accurate temperature feedback from different motor locations. Compared with traditional optical fiber sensing multiplexing systems, it can simultaneously detect the reflection spectrum change signals caused by temperature variations in each spatial mode, enhancing the sensing capacity of the sensor system and reducing the cost of the multiplexing system.

2. Experimental Principle and Setup

To study the multi-channel temperature optical sensing performance of an electric motor based on FMF spatial mode division sensing multiplexing topology structure, the experiment employed four spatial modes LP₀₁, LP₁₁, LP₂₁, and LP₀₂ for FBG division multiplexing. As illustrated in Fig. 1, the system mainly consists of a wide spectrum light source, an FMF circulator, a mode-selective photonic lantern [24], an FBG array, a spectrum analyzer, and a measured motor. The specific work flow of the system is as follows: A broad-spectrum light source's single-mode pigtail is eccentrically fusion spliced with the pigtail of port 1 of the FMF circulator by 2 μm, effectively exciting the fundamental mode LP₀₁, as well as higher-order spatial modes LP₁₁, LP₂₁, and LP₀₂. Subsequently, the multi-path spatial modes are outputted through port 2 of the FMF circulator, entering the photonic lantern for spatial mode transformation. They are converted to the corresponding fundamental mode LP₀₁, entering the FBG topological array. Under varying motor speeds and loads, the temperature changes cause alterations in the reflected spectra of the FBG sensors carried by different spatial modes. In this setup, the reflected spectra from the FBG topological array are directed back to a photonic lantern, which converts them into corresponding high-order spatial modes for multiplexing. The multiplexed spatial modes are then channeled through port 2 into an FMF circulator, with the output from port 3 entering a spectrometer for spectral detection and acquisition. Finally, the central wavelength of FBG is determined by finding the highest intensity point (wave peak) in the FBG reflection spectrum carried by LP₀₁, LP₁₁, LP₂₁, and LP₀₂ modes through the central wavelength positioning. Then, according to the FBG linear fitting expression carried by each mode, the corresponding temperature change value of each point of the motor is calculated, and the multi-point synchronous detection of the motor temperature is realized.

Within the array, the initial central reflection wavelengths of the fiber Bragg grating sensors are respectively:

$$\lambda_i = 2\Lambda_i n_{\text{eff}_i} \quad (1)$$

where λ_i denotes the initial reflection center wavelengths of FBG carried by the corresponding spatial modes LP₀₁, LP₁₁, LP₂₁, and LP₀₂, respectively. The $i = 1, 2, 3, 4$ represents the LP₀₁, LP₁₁, LP₂₁, and LP₀₂ modes. Meanwhile, Λ_i refers to the grating pitch

of each FBG, and n_{eff_i} signifies the effective refractive index of each FBG. In the array,

the FBG sensors are embedded in different parts of the stator windings of the induction

motor using epoxy resin, as illustrated in Fig.1. Specifically, FBG₁ and FBG₃ are encapsulated near the fan end, where FBG₁ is fixed within the inner coil with the insulation material removed, and FBG₃ is affixed to the slot wall. On the other hand, FBG₂ and FBG₄ are encapsulated near the output end of the shaft, with FBG₂ fixed inside the inner coil and its insulation material resealed, and FBG₄ is affixed to the slot wall. The change in the central wavelength of the reflected spectrum of the i th FBG sensor, resulting from a variation in the ambient temperature, can be defined as follows:

$$\frac{\Delta\lambda_{mn_i}}{\lambda_{mn_i}} = (\alpha_{TE} + \alpha_{TO})\Delta T_i \quad (2)$$

where $\Delta\lambda_{mn_i}$ represents the central wavelength shift of the FBG carried by the i th

spatial mode. The α_{TE_i} and α_{TO_i} respectively denote the thermal expansion

coefficient and the thermo-optic coefficient of FBG. Furthermore, the ΔT_i signifies the amount of temperature change in the environment where the i th FBG is situated.

The proposed method utilizes the spatial mode dimension of FMF, and multiple FBG channels are allocated to the optical paths carried by different LP spatial modes to realize parallel multiplexing of multiple FBG sensors. When a single FBG unit is damaged, FBG carried by other spatial modes can continue to work, which solves the problem that the reliability of traditional WDM serial topology is relatively low.

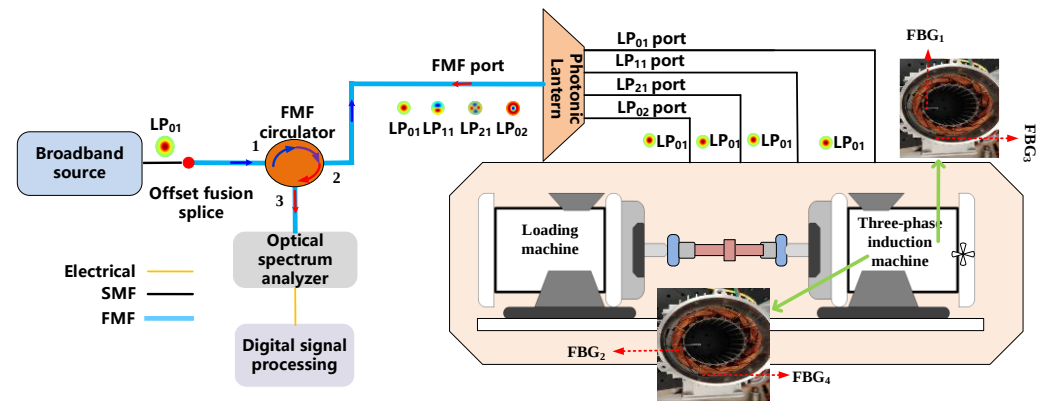


Figure 1. Motor stator winding synchronous temperature monitoring system based on FMF spatial mode diversity FBG multiplexing.

3. Experiment Results and Analysis

To achieve precise detection of motor temperature, it is first necessary to calibrate the FBG sensors. This involves measuring the variations in the reflected spectral wavelengths of the FBGs as a function of temperature, and deriving the requisite temperature-wavelength fitting curve from these measurements [3, 25]. It can be seen from Eq.(2) that λ_{mn_i} , α_{TE_i} and α_{TO_i} are inherent properties of FBG, and when the temperature ΔT_i changes, the change of FBG's reflected wavelength is λ_{mn_i} . According to this principle, an FBG calibration experiment is conducted, using a temperature control system with a precision of 0.1°C. In this experiment, the temperature range is set from 20°C to 100°C, with each 20°C increment serving as a data point. The central wavelength variations of FBG₁, FBG₂, FBG₃ and FBG₄ carried by four spatial modes is measured, respectively. Subsequently, the data pertaining to the FBG reflected spectra are subjected to linear fitting and cubic fit,

respectively, and linear fit and the cubic fit results are shown in Fig. 3. Through comparative analysis, it can be seen that the fitting degree R^2 of linear fitting is basically the same as that of cubic fitting. Because the linear fitting calculation is relatively simple, it is more convenient to accurately convert the measured reflected wavelength shift into temperature. From the analysis of the data, it is discernible that each FBG exhibits a certain linearity. The slope of the fitting curve represents the sensitivity of the sensor to temperature change, and the FBG sensitivity carried by the LP₀₁, LP₁₁, LP₂₁, and LP₀₂ mode is 0.0107 nm/°C, 0.0106 nm/°C, 0.0097 nm/°C, and 0.0116 nm/°C, respectively. The linear fitting curves derived from the data obtained from each FBG can be utilized to accurately translate the detected wavelength shifts into temperature readings in subsequent testing.

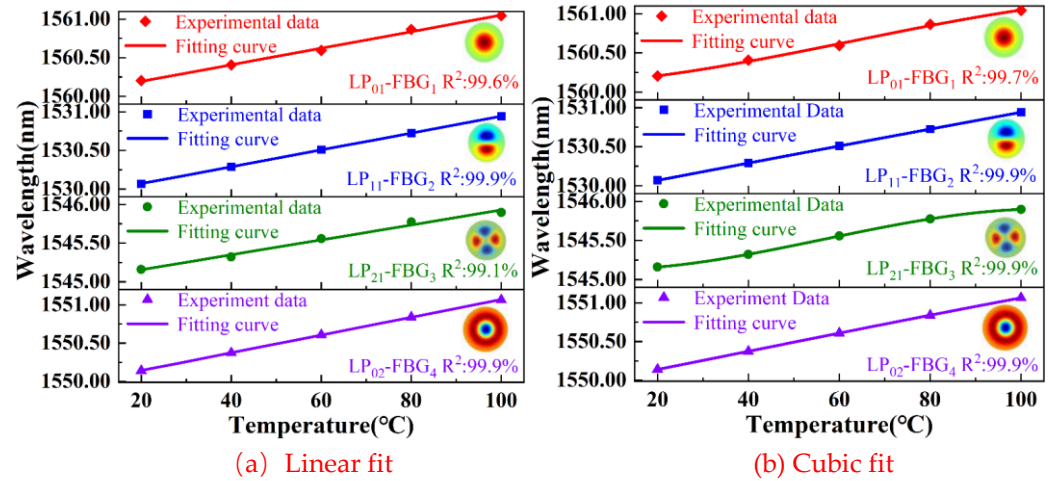


Figure 2. FBG Sensor calibration test data.

Initially, tests are conducted on an unloaded motor operating at various rotational speeds. The temperature variations in different parts of the stator windings at unloaded motor speeds of 1k rpm, 1.5k rpm, and 2k rpm, stabilized over 25 minutes, are measured using a modal diversity FBG multiplexing system. The results are displayed in Fig. 3. Analysis of the figure reveals that temperatures recorded by FBG₁, FBG₂, FBG₃, and FBG₄, carried by LP₀₁, LP₁₁, LP₂₁, and LP₀₂ spatial modes, respectively, increase with the motor speed and over time. Initially, the temperature rise is rapid, but it gradually stabilizes later on. Specifically, the FBG₁ carried by LP₀₁ mode is located near the fan, inside the stator winding copper coil with intact insulation. Thus, it initially exhibits efficient heat dissipation and a slower temperature rise. After 25min, the no-load operation of 1k rpm, 1.5k rpm, and 2k rpm increased by 5.3°C, 7.6°C, and 8.3°C respectively. The FBG₂, carried by the LP₁₁ mode and located in the copper coil of the stator winding far from the fan, shows a rapid temperature rise and significant temperature differential due to damaged insulation, with increases of 18.6°C, 20.8°C, and 23°C at the respective speeds. The FBG₃, associated with the LP₂₁ mode and positioned near the fan on the slot wall without direct contact with the stator winding, exhibits the least noticeable temperature changes, with increases of 3.3°C, 4.2°C, and 5.7°C. Finally, the FBG₄, carried by the LP₀₂ mode and situated on the slot wall away from the fan, experiences a relatively rapid initial rise, but the total temperature change is less than that within the stator winding copper coil, showing increases of 4.8°C, 6.2°C, and 6.9°C at the respective speeds. Through the above analysis, it can be seen that the multi-point temperature change monitoring of stator windings of the motor can be realized by FBG bearing in each spatial mode.

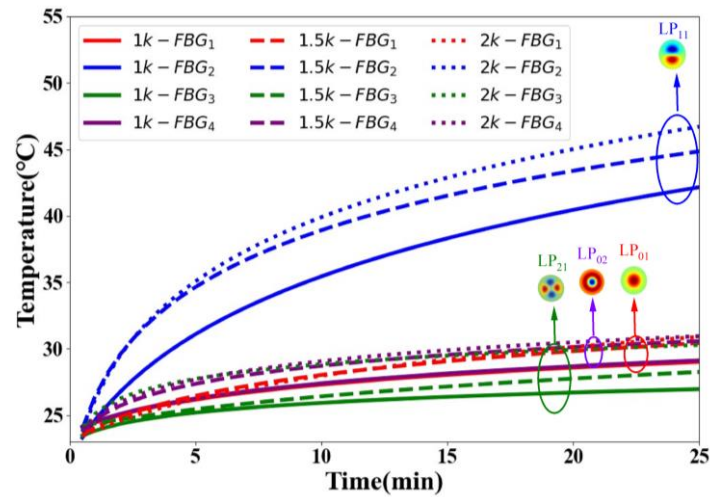


Figure 3. FBG dynamic temperature change curves are carried by different spatial modes under different rotational speeds.

Further tests and analyses are conducted on the temperature distribution at different locations of a three-phase induction motor operating unloaded at various speeds for 25 minutes. The results are presented in Fig. 4. The analysis reveals significant temperature changes in FBG₁ and FBG₂, located within the stator winding copper coils, as the rotational speed increases. Specifically, the temperatures at these points rise from 27.9°C and 31.6°C at 250 rpm to 36.9°C and 50°C at 2.5k rpm, corresponding to changes of 9.1°C and 18.4°C, respectively. Conversely, FBG₃ and FBG₄, situated on the slot wall, exhibit less pronounced temperature changes with increasing speed. Overall, their temperatures rise from 27.1°C and 28.8°C at 250 rpm to 32.1°C and 31.6°C at 2.5k rpm, showing changes of 4.9°C and 2.8°C, respectively. In summary, the analysis indicates that a multi-channel optical temperature sensing system for motors, based on spatial mode division, can achieve real-time synchronous monitoring of working temperature changes in different parts of the motor stator winding through the parallel topology of FBGs carried by spatial modes. This confirms the feasibility of this approach.

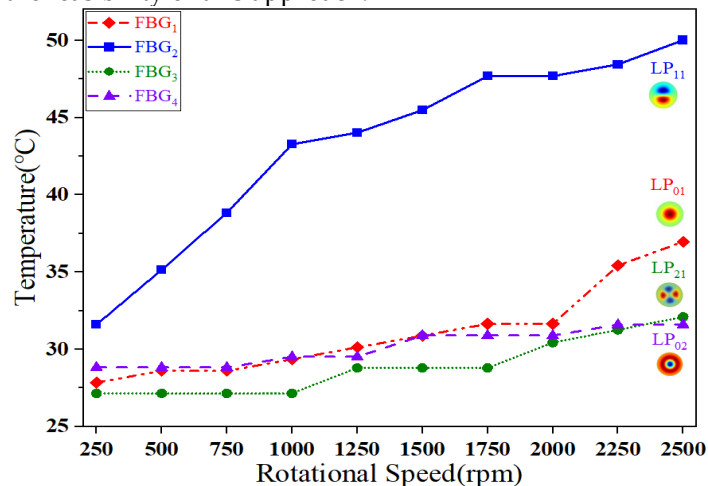


Figure 4. Temperature distribution of stator winding points after 25min stable operation at different speeds under no-load conditions.

Secondly, an analysis of the temperature changes in the motor under load conditions was conducted, with temperature change tests carried out at 1k rpm and 2 k rpm, both under no load and with a 5 kg load. Similarly, the temperature variation process in different parts of the stator winding of the three-phase induction motor is measured during stable operation up to 25 minutes. Fig.5 (a) shows the dynamic temperature changes at

the location of sensor FBG₁ carried by LP₀₁ mode. Under a 5kg load at 1k rpm, there is a temperature rise of 6.1°C compared to the no-load condition. At 2k rpm, the 5kg load caused an 11.9°C increase in temperature. The faster the speed, the greater the load torque, resulting in higher copper and iron losses and therefore a greater rise in temperature. Fig. 5 (b)-(d) show the temperature changes at the FBG₂, FBG₃, and FBG₄ sensors in the LP₁₁, LP₂₁, and LP₀₂ modes, respectively. At 1 k rpm with a 5 kg load, the temperature increases are 4.4°C, 3.3°C, and 1.4°C, respectively, while at 2 k rpm with a 5 kg load, they are 4.5°C, 5.5°C, and 1.9°C, respectively. Similarly, the greater the load torque, the greater the copper and iron losses, and the more significant the temperature rise, which is consistent with actual operating conditions.

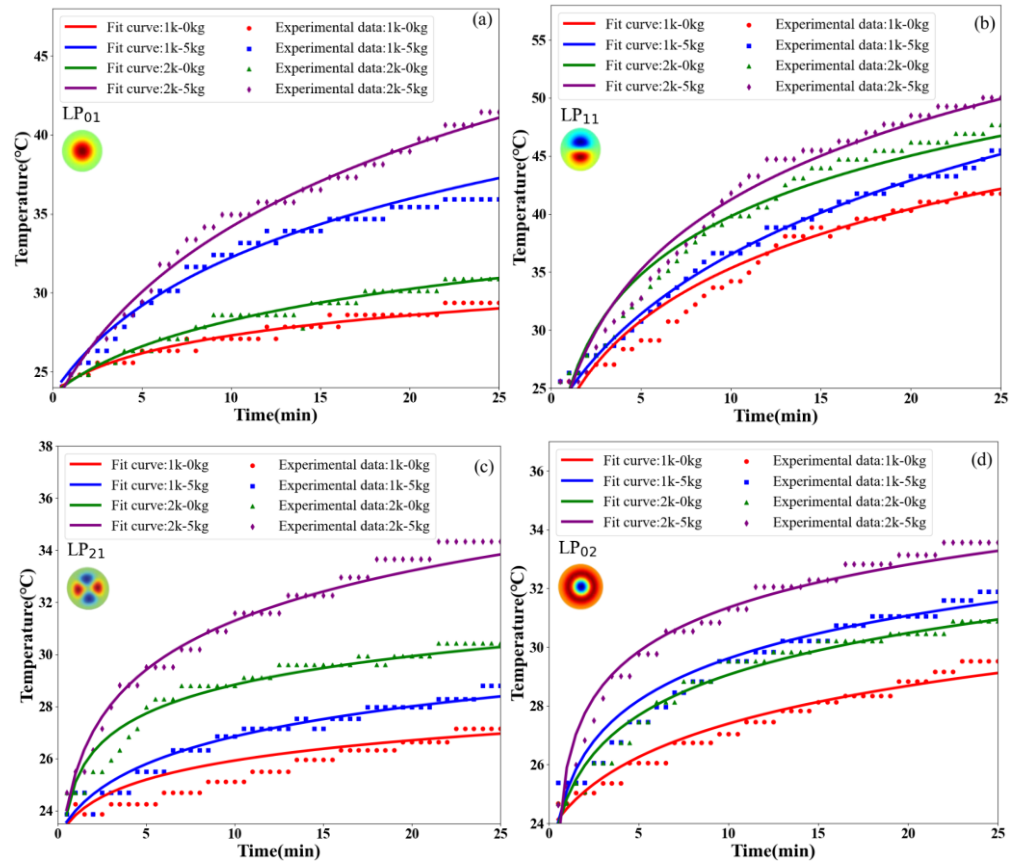


Figure 5. FBG temperature variation process carried by different spatial modes under different load operation conditions. (a) LP₀₁ mode, (b) LP₁₁ mode, (c) LP₂₁ mode, (d) LP₀₂ mode.

Further tests are conducted to assess the temperature changes of FBGs carried by different spatial modes at 1 k rpm, 1.5 k rpm, and 2 k rpm, as well as under 0 kg, 3 kg, and 5 kg load conditions, running up to 25 minutes until a stable state is reached, as shown in Fig. 6. FBGs in LP₀₁ and LP₂₁ modes, FBG₁ and FBG₃, have similar packaging locations, resulting in identical temperature increase trajectories. However, since FBG₁ is located inside the motor winding, its temperature rise is more pronounced. At different speeds and under a 5kg load, FBG₁ showed temperature increases of 6.2°C, 8.5°C, and 10.4°C, respectively, while FBG₃ showed increases of 1.7°C, 1.6°C, and 3.9°C. Similarly, in the LP₁₁ and LP₀₂ modes, FBG₂ and FBG₄ have closely situated packaging locations, leading to identical temperature rise trajectories. Under a 5 kg load, FBG₂ exhibited temperature increases of 2.2°C, 2.2°C, and 3.1°C, respectively, while FBG₄ showed increases of 2.1°C, 1.6°C, and 2.7°C.

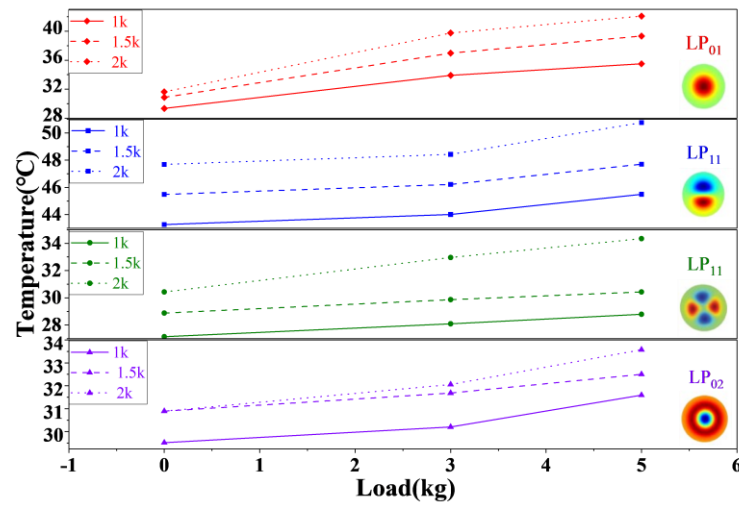


Figure 6. Temperature distribution at various points of the stator winding during stable operation under different speeds and load conditions.

Finally, the operation of the three-phase induction motor under common working modes at different times with different speeds and loads is carried out. Specifically, the motor operated in three separate phases: 1.5 k rpm at 3 kg, 1 k rpm at 0 kg, and 2 k rpm at 5 kg, each for 25 minutes, and then in another set of phases at 2 k rpm at 5 kg, 250 rpm at 0 kg, and 2 k rpm at 5 kg, each also for 25 minutes. The test results are shown in Fig. 7, presenting the time-wavelength and time-temperature variation curves of FBGs in different spatial modes under various working conditions. During the operation at 1.5 k rpm at 3 kg, 1 k rpm at 0 kg, and 2 k rpm at 5 kg, the sensors FBG₁, FBG₂, FBG₃, and FBG₄ in the LP₀₁, LP₁₁, LP₂₁, and LP₀₂ modes respectively, the recorded temperature rises to 35.4°C, 45.5°C, 28.8°C, and 28.9°C after the first phase. Due to the minimal decrease in speed during the second phase and the heat generated from copper and iron losses in the first phase, the sensor temperatures remained relatively stable. By the end of the third phase, temperatures reached 44.1°C, 50.4°C, 34.5°C, and 33.8°C respectively. During the operation at 2k rpm_5kg, 250 rpm_0kg, and 2k rpm_5kg, the sensors showed temperature fluctuations due to the significant reduction in speed and load in the middle phase, eventually reaching 43.6°C, 50.1°C, 34.3°C, and 34.2°C after the final phase. Moreover, since the conditions of the third phase in the first set and the first and second phases in the second set are the same (2k rpm-5kg for 25 minutes), the temperatures achieved are similar to those in Figure 6 for the 2k rpm-5kg test, further validating the reliability of the experiment.

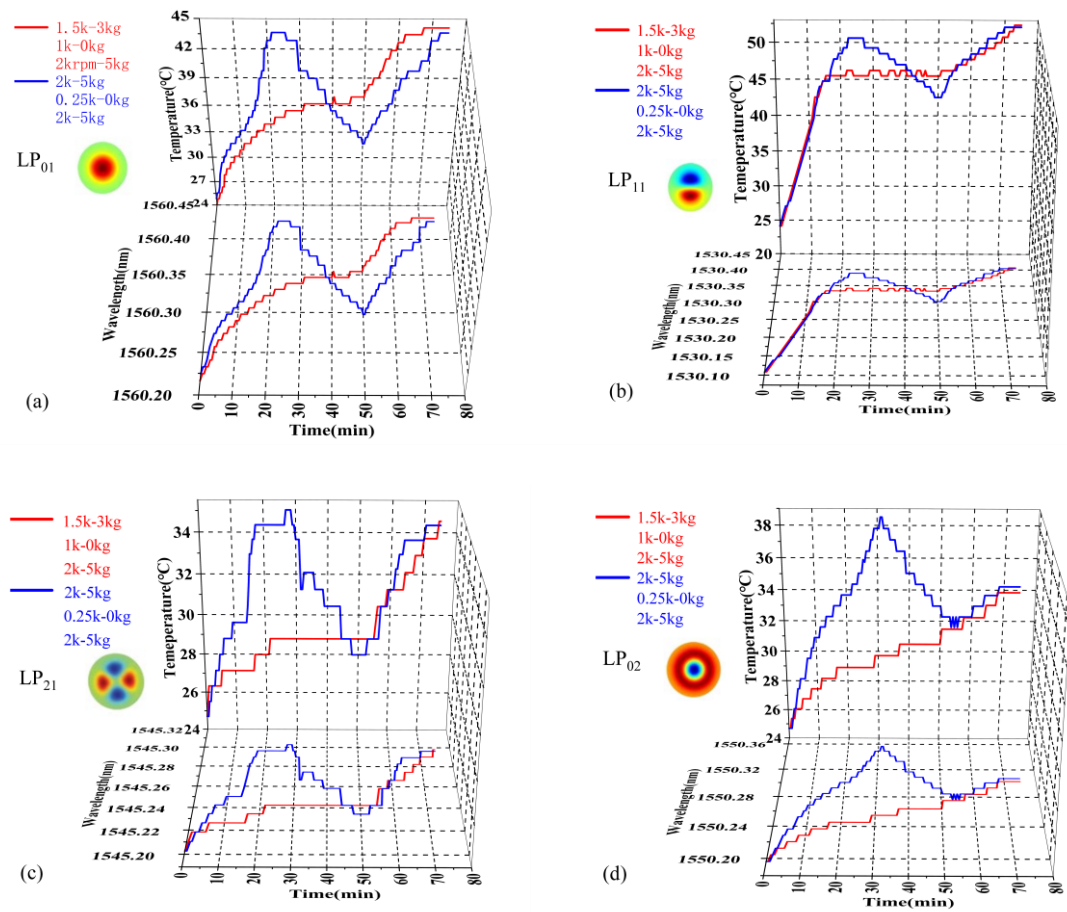


Figure 7. Dynamic temperature variation curves of stator windings in each mode under multi-speed operation. (a) LP₀₁ mode, (b) LP₁₁ mode, (c) LP₂₁ mode, (d) LP₀₂ mode.

To conduct a more comprehensive analysis of the FBG multiplexing performance based on the FMF mode diversity, an in-depth examination of the monitoring fluctuations of each spatial mode under different operational conditions of the motor is performed. For ease of understanding, the experimental conditions mentioned above are numbered. Experiments under no-load, 3kg, and 5kg loads at three different speeds of 1k rpm, 1.5k rpm, and 2k rpm were designated as experiments 1 to 9. The multi-speed conditions of 1.5k rpm_3kg, 1k rpm_0kg, 2krpm_5kg are labeled as experiment 10, and 2k rpm_5kg, 250 rpm_0kg, 2k rpm_5kg as experiment 11. The performance data of FBG₁, FBG₂, FBG₃, and FBG₄ carried by LP₀₁, LP₁₁, LP₂₁, and LP₀₂ modes, are illustrated in Fig.8. In this figure, the red and blue broken lines represent the maximum temperature jump (When the monitored temperature changes greater than 1 °C, it is called a jump) and fluctuations (The operating conditions of the motor do not change, and the temperature rises or falls that cannot be maintained), respectively, corresponding to the right Y-axis. The red and blue histograms represent the number of maximum temperature jumps and fluctuations, corresponding to the left Y-axis. Since data is recorded every 30 seconds, experiments 1-9 had a total of 50 data points over 25 minutes, and experiments 10-11 had 150 data points over 75 minutes. In the LP₀₁ mode, abnormal data with jumps constituted 1.6% of the total, with a maximum temperature jump of 3.112°C. For high-order modes like LP₁₁, LP₂₁, and

LP₀₂, the proportions of data with jumps are 4.5%, 0.6%, and 0.8% respectively, with maximum temperature jumps of 3.7°C, 2.4°C, and 2.8°C. The higher percentage and larger temperature jump in LP₁₁ can be attributed to its location on the inner copper winding, where the insulation layer is stripped, leading to a wide range of temperature changes and a large number of jumps. In summary, the performance of all modes is basically the same in this aspect. In terms of fluctuations, the high-order modes like LP₁₁, LP₂₁, and LP₀₂ showed more fluctuations compared to the LP₀₁ mode. There are 5 fluctuations in the fundamental mode, and the maximum jump temperature is 0.8°C. In the high-order modes such as LP₁₁, LP₂₁, and LP₀₂, the number of fluctuations reached 8, 6, and 10 times respectively, and the maximum jump temperature is 0.7°C, 0.8°C, and 0.8°C, respectively. This could be due to mode crosstalk in the few-mode fiber and the photonic lantern, suggesting that the measurement stability of high-order modes might require more data for validation. Despite this, the inclusion of high-order modes could expand channel capacity, offering a level of performance comparable to the LP₀₁ mode.

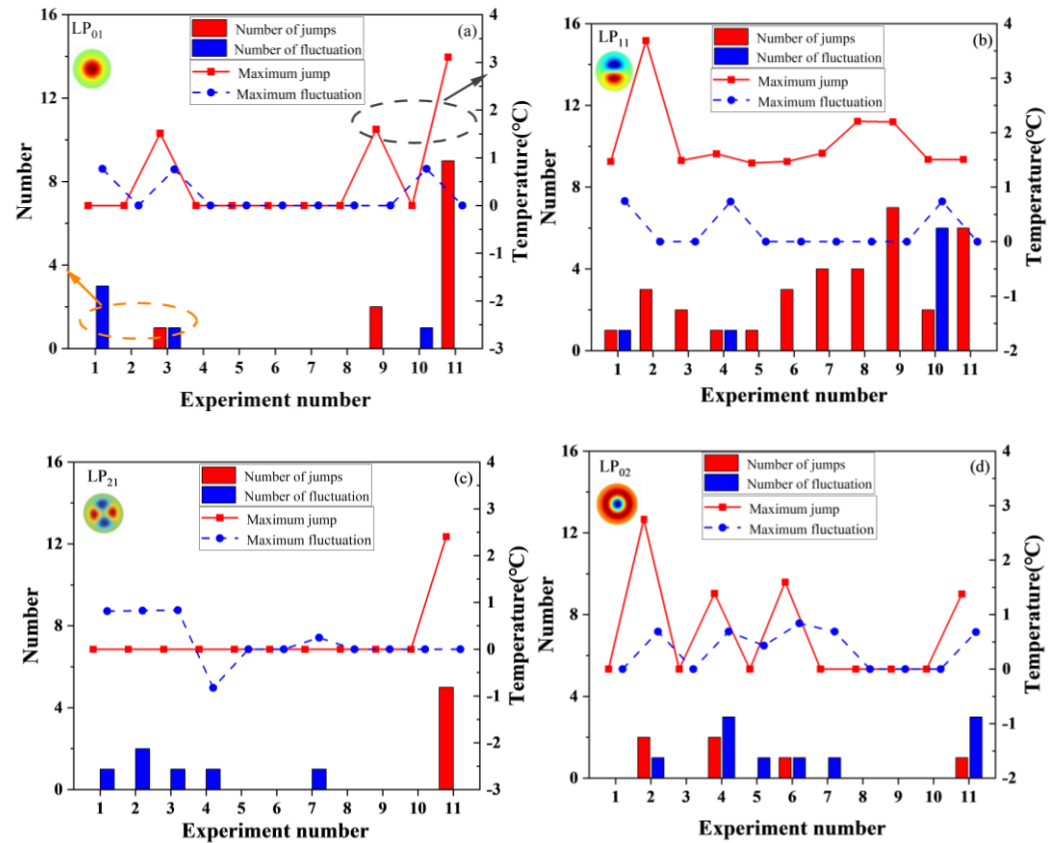


Figure 8. Performance analysis of FBG sensing multiplexing with spatial mode diversity. (a) LP₀₁ mode, (b) LP₁₁ mode, (c) LP₂₁ mode, (d) LP₀₂ mode.

4. Conclusions

This paper introduces a novel multi-point optical temperature sensing method for motors based on utilizing FMF spatial mode division. By embedding FBGs carried on different spatial mode paths into various positions of the motor, it achieves synchronous multiplexed temperature monitoring of the stator winding. As a proof of concept, a mode division motor temperature FBG multiplexing system based on a photonic lantern is

established, using the fundamental mode LP_{01} and higher-order spatial modes LP_{11} , LP_{21} , and LP_{02} as examples to conduct multiplexed experiments for multi-point temperature sensing of the motor stator. The study tests the dynamic temperature changes at different positions of the motor stator under various conditions for a three-phase induction motor at three different speeds of 1k rpm, 1.5k rpm, 2k rpm with no load, 3 kg load, and 5 kg load, as well as at three specific speed-load combinations of 1.5k rpm_3kg, 1k rpm_0kg, 2k rpm_5kg, and another set of three speed-load conditions of 2k rpm_5kg, 250 rpm_0kg, 2k rpm_5kg. The measurement results of each spatial model are compared and analyzed. The experimental results indicate that the motor multiple-channel temperature optical sensing system based on the fundamental spatial mode LP_{01} and higher-order spatial modes LP_{11} , LP_{21} , and LP_{02} can achieve real-time synchronous monitoring of the working temperature changes at different parts of the motor stator winding. Among them, the jump abnormal data of LP_{01} mode accounted for 1.6%, while jump abnormal data of the high-order modes LP_{11} , LP_{21} , and LP_{02} accounted for 4.5%, 0.6%, and 0.8%, respectively. The reason for the higher rate of jump abnormal data in the LP_{11} mode is that the testing area is on the internal copper wire winding with the insulation layer stripping, leading to a larger range of temperature changes and consequently more frequent jumps. In terms of fluctuations, while the fundamental mode LP_{01} showed 5 instances of fluctuation, the high-order modes LP_{11} , LP_{21} , and LP_{02} exhibited 8, 6, and 10 instances of fluctuations, respectively. The higher-order modes are more prone to fluctuations due to mode crosstalk in FMMs and photonic lanterns. In summary, the scheme can simultaneously detect the temperature change of different positions of the motor through various spatial modes, enhance the sensing capability of the sensor system, reduce the cost of the multiplexing system, and have high reusability and reliability. This scheme provides a novel approach for multiplexed sensing in monitoring multiple physical fields for motors. However, how to effectively eliminate the impact of mode crosstalk and improve the stability of measurements in high-order spatial modes still requires further in-depth research.

Author Contributions: Conceptualization, methodology, and writing—original draft preparation, Feng Liu; software, and validation, Tianle Gu; formal analysis, investigation, and resources, Weicheng Chen.

Funding: This work was supported in part by the National Natural Science Foundation of China under Grant No. 62105246, Zhejiang Provincial Natural Science Foundation of China under Grant No. LY23F050003.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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