Method for reducing the influence of crosstalk on quasi-distributed sensing network with time-division multiplexing fibre Bragg gratings

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Abstract. A serial time-division multiplexing (TDM) quasi-distributed sensing array based on the ultra-weak reflection fibre Bragg gratings (FBGs) has been widely used in various areas. However, multiple reflections and shadow effect between FBGs with the same centre wavelength will accumulate as the number of gratings multiplexed increases, which will cause a significant increase in crosstalk of the reflection spectrum and will seriously affect the accuracy of the measurement results. In this paper, we theoretically analyse the instability of the results caused by multiple reflections and shadow effect, and propose a layer-by-layer compensation method to suppress crosstalk and improve the stability of the results. About 4000 FBGs with a reflectivity of 0.01% were multiplexed in the experimental system, and we measured the fluctuation of the centre wavelength of the grating at different distances to prove the effectiveness of the method we proposed. The experimental results show that the method proposed in this paper can greatly reduce the shift of the centre wavelength of the reflection spectrum and improve the stability of the system.

1. Introduction

A serial time-division multiplexing (TDM) quasi-distributed sensing network has been applied to many areas, such as temperature [1], [2] and strain [1], [3], which provides several distinguishing advantages of high sensitivity, low-cost and high multiplexing capability [4]. The TDM method uses different time delays between reflected pulses to distinguish gratings with the same centre wavelength, and can alleviate the spectral bandwidth issue [6]. We multiplexed thousands of FBGs on a single fibre as intrinsic reflectors to form a sensing array without any other optical fibre equipment or splicing points [5], [7].

However, the multi-reflection (MR) and shadow effect between the FBGs will become severer with the number of multiplexed FBGs in an array increases, which exacerbate crosstalk and instability of demodulation result [8]. Although we have used FBGs with reflectivity of 0.01%, when the number of multiplexed FBGs exceeds 2000, significant crosstalk can still be seen from the reflected spectrum.

The method of suppressing the crosstalk in TDM is the key technology to improve the TDM capability. In 1989, Kersey et al. [9] came up with some basic principles about the MR induced crosstalk and presented the relationship among the crosstalk value, the reflectivity of the FBGs and the multiplexing sensor number. C.C.Chan et al [10]. investigated the shadow effect in TDM and gave the
spectral due to the shadow effect and MR caused by multiplexing of FBGs with the same central wavelength. Ref. [3]. Proposed a serial TDM sensor network based on ultra-weak FBGs, in which the ultra-low reflectivity of the gratings makes it possible to multiplex over 1000 gratings along a single optical fibre. Ref. [11]. [12]. Introduced a layer-peeling algorithm to reduce the MR in the TDM system based on FBGs and the experimental results showed that a 15-20dB improvement can be achieved. Ref. [7]. Presented an interference synthesis (IS) method to reduce the crosstalk for a 2-TDM inline sensor array and the measured crosstalk has achieved -40dB with the FBG reflectivity of 5%. Research on crosstalk suppression mainly focuses on the application of layer-peeling algorithm recently. But the existing peeling algorithm is only suitable for small-scale test systems. What we need to solve is the crosstalk in large-scale and long-distance ultra-weak fibre grating sensing system in which the number of multiplexed gratings reaches 2000 or even more than 2000.

Based on the idea of suppressing crosstalk layer by layer, a new crosstalk suppression algorithm is proposed in this paper. The reflectivity of the grating is measured first, and then based on the principle of MR and shadow effect, a layer-by-layer compensation method is used to suppress the influence of crosstalk on the demodulation solution results. Under the premise of using ultra-low reflectivity FBG, using this algorithm can further suppress crosstalk and greatly improve the stability of the measurement results. It can be seen from the experimental results that before using the algorithm proposed in this paper, the centre wavelength drift amplitude is 0 to 0.09nm, and it can be controlled within 0.04nm after using this algorithm.

2. Theory and Method

2.1. Principles of the Multi-Reflection Induced Crosstalk

When multiple FBGs are multiplexed on an optical fibre, a structure similar to a resonant cavity will be formed between adjacent FBGs, and incident light will be reflected multiple times in it. When the light pulse signal passes through the upstream grating, the light pulse will be reflected between the gratings multiple times and reach the detector at the same time as the reflected light of the downstream grating, which will cause the distortion of the measurement spectrum, reduce the signal-to-noise ratio, and reduce the measurement accuracy. The principle diagram of the first-order multiple reflection is shown in Figure 1

![Figure 1. The principle diagram of the first-order multiple reflection](Image)

As shown in the figure 1, compared with normal reflected light, one more back and forth reflection between two gratings is called first-order reflection. The multiple reflection signal above the second-order is very weak, so we only consider the influence of the first-order reflection signal. We assume that the reflectivity of all the gratings in the grating array is the same, and their reflectivity is \( R(\lambda) \). And the light source intensity is \( I_0(\lambda) \). The first-order reflection of the grating is deduced separately, and the first-order reflection formula of the ith grating can be obtained as [13]:
\[ G_i(\lambda) = \frac{(i-1)(i-2)}{2} R^3(\lambda) I_0(\lambda)(1 - R(\lambda))^{2(i-2)} \]  

(1)

It can be known from equation (1) that the lower the reflectivity of the grating, the smaller the number of multiplexed gratings, the smaller the impact of crosstalk on system performance.

2.2. Shadow effect analysis

When the pulsed light propagates along the fiber grating array, each grating in the path will reflect a part of the light back, which will affect the reflection spectrum of the back-end grating. The optical power at the center wavelength of the grating in the reflection spectrum will decrease, resulting in a depression phenomenon. As the number of grating multiplexing increases, the depression phenomenon will gradually increase. When the reflectivity of the ultra-weak gratings in the grating array is the same, the reflection signal of the nth FBG can be expressed as:

\[ G_n(\lambda) = R(\lambda) I_0(\lambda)(1 - R(\lambda))^{2(n-1)} \]  

(2)

It can be seen from this formula that when the reflectivity of the fiber is low and the number of multiplexed gratings is small, the influence of the shadow effect on the spectrum is relatively weak. Although, ultra-weak FBG array is used in our experiment system, because the number of multiplexed number is too large, more accurate results can be obtained by considering the shadow effect.

2.3. Methods of reducing crosstalk

The layer peeling algorithm is mainly used to solve the inverse problem of FBG at first. It calculates the structure parameters of grating through the reflection spectrum of grating. In order to reconstruct the structural parameters of the FBG, the grating should be divided into discrete layers. Starting from the initial conditions, we first obtain the structural parameters of the first layer, and then analyse the second layer according to the transmission characteristics of the light field. In the second layer, the first layer has no effect on the parameters of the subsequent layers. In this way, the influence of the first layer can be stripped off, the second layer can be regarded as the first layer.

Based on the idea of suppressing the influence of the upstream grating on the downstream grating layer by layer, an algorithm to reduce the influence of crosstalk and improve the demodulation stability of the quasi-distributed sensing network by means of layer-by-layer compensation is proposed in this paper. The structure of the fiber grating array is shown in Figure 2.

![Figure 2. The structure of the fiber grating array](image)

Where \( I_{in,i} \) are the input light of each grating, \( I_{out,i} \) are the output light of each layer after reflected by fiber grating.

If only the influence of MR on the result is considered, the crosstalk only exists in the reflected light of the third grating and subsequent gratings. We assume that the reflected light intensity reflected back from the ith grating in the FBG array is \( R_i(\lambda) \). If all gratings in the FBG array have the same reflectivity, and regardless of the interference from the external environment, we can get the compensated reflected light intensity as:

\[ R_i(\lambda) = R_i(\lambda) - \frac{(i-1)(i-2)}{2} R^3 I_0(\lambda)(1 - R)^{2(i-2)} \]  

(3)

Where \( R \) is the reflectivity of all gratings in the fiber grating array, and \( I_0(\lambda) \) is the initial light intensity of the fiber grating array.
However, in actual measurement, the reflectivity of each grating in the fiber grating array is different, and the center wavelength of each grating is also slightly different, so the above formula cannot be directly used for calculation. We need to use the measured reflection spectrum data of the previous grating to suppress the influence of crosstalk in the reflection spectrum of the subsequent grating layer by layer. Therefore, we can obtain the reflected light intensity after suppressing crosstalk as:

$$R_i(\lambda) = R_i(\lambda) - \sum_{j=2}^{i-1} jR_j(\lambda)R_j^2$$  \hspace{1cm} (4)

Where $R_j$ is the reflectivity of the gratings in the grating array.

When calculating the reflected light intensity of the downstream grating by this formula, we need to introduce the reflected light data of all upstream gratings. By cyclic calculation layer by layer, we obtain the reflected light intensity data of all gratings in the grating array after suppressing multiple reflection crosstalk.

When the reflectivity of FBG is extremely low, the shadow effect has almost no influence on the reflectance spectrum data. In the system adopted in this paper, the grating with reflectivity of 0.01% is used, which makes the shadow effect have little effect on the reflection spectrum. However, due to the large number of multiplexed gratings, in order to obtain more accurate spectral data, we still consider the impact of shadow effects on the data processing process.

So when we consider the multiple reflection and shadow effect at the same time, we can get that the reflected light intensity of the ith sensor is:

$$R_i(\lambda) = R_i(\lambda) - \sum_{j=2}^{i-1} jR_j(\lambda)R_j^2 + \sum_{j=1}^{i-1} R_j(\lambda)R_i(1 - R_i)$$  \hspace{1cm} (5)

Through the above method, it is possible to obtain spectral data after suppressing multiple reflection crosstalk and shadow effect, and optimize the performance of the quasi-distributed wavelength demodulation system.

3. **Experimental results and discussion**

In this part, we build a quasi-distributed time division multiplexing FFP sensor array. The degree of the crosstalk and the demodulation instability of our system were tested. The effectiveness of the algorithm proposed in this paper in suppressing crosstalk and improving demodulation stability is verified.

Figure 3 shows the schematic diagram of the experimental system. A swept frequency laser is used as the light source to the system, and the wavelength scan range in the experiment is 1548nm to 1552nm. The light is pulsed by an SOA with the frequency of 250 MHz and the pulse width is 20 ns.
The gratings in the FBG array we used were written according to the same parameters, so we assume that their parameters are the same. We need to measure the reflectivity of grating before experiment. [14]. We continuously measure the centre wavelength of the grating 50 times, and determine the stability of the demodulation result by calculating the maximum difference and standard deviation of the 50 results. In the experiment, we measured the spectral data of the gratings numbered 501 to 600, 1501 to 1600, 2501 to 2600, 3501 to 3600, and compared the stability of the demodulation results before and after suppressing crosstalk to determine the effectiveness of the algorithm proposed in this paper.

The spectrum comparison before and after suppressing crosstalk is shown in the figure below:

![Figure 4. The spectral contrast before and after crosstalk elimination](image)

The figure 5 and 6 show the maximum shift and the standard deviation of the centre wavelength shift of each grating before and after crosstalk suppression respectively.

![Figure 5 The maximum shift of the centre wavelength of each grating before and after crosstalk suppression](image)
Figure 6 The standard deviation of the centre wavelength drift of each grating before and after crosstalk suppression

The centre wavelength shifts of the 450, 900, 1350, 1800, 2250, 2700, 2150, and 3600 gratings are shown in the figure below. We can see the overall effect of the algorithm proposed in this paper on the crosstalk suppression of gratings at different positions.

Figure 7 Overall crosstalk suppression effect diagram

The experimental results show that the MR in the grating array will cause crosstalk signals, and will also lead to unstable demodulation results. Facts have proved that the method proposed in this paper is feasible for suppressing crosstalk.

At the same time, there are some factors that will affect the crosstalk suppression effect of this method. First of all, we only measure the parameters of the first grating. For other gratings, we use the reflectivity and centre wavelength of the first grating to bring them into the calculation. Although all the gratings in the FBG array we use are written according to the same parameters, there are still some differences in the parameters, which will affect the result of crosstalk suppression. Secondly, we only considered the crosstalk generated at the grating, but the transmission fibre between the gratings also has a certain impact on the reflection spectrum.

It is impossible to eliminate errors caused by the difference in reflectivity and centre wavelength of the grating. In the experiment, we can only choose better quality gratings to ensure that the parameters of all gratings on the fibre grating array are as consistent as possible. There is no perfect solution to the
problem of the incorrect position of the back-end fibre grating, which involves the contradiction between the number of multiplexed grating and measurement accuracy. We can only obtain more accurate position information by adjusting the threshold or intensity of the incident light, thereby obtaining accurate grating reflection spectrum data. Regarding the errors caused by the transmission fibre, this will also be our next research content. We consider the method of transmission matrix to eliminate this part of the error.

4. Conclusion
In summary, we discussed the influence of multiple reflection and shadow effects of FBG array time division multiplexing on the demodulation results of distributed sensor networks. An algorithm for reducing MR crosstalk and improving the demodulation stability of the quasi-distributed time division multiplexing system is proposed. The experimental results show that under the premise of using a grating with a reflectivity of 0.01%, the algorithm proposed in this paper can have a significant crosstalk suppression effect.

The feasibility of this method has been proved. The algorithm is based on the principle of multiple reflection and shadow effects, and provides a practical means to eliminate crosstalk. The principle of the algorithm can be extended to FFP sensor arrays with more TDM channels and more different application scenarios, which is also our further goal in the research of FBG sensor arrays.

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