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Improvement of spatial resolution of Brillouin optical time domain reflectometer using spectral decomposition

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Brillouin optical time domain reflectometer (BOTDR) has been used for strain and temperature measurement and health monitoring in infrastructural systems. However, the spatial measurement resolution of BOTDR cannot yet meet the measuring needs of some specific local strains, such as the strain caused by a narrow crack or fissure in structures. In this paper, a spectral decomposition method is proposed and used for improving the spatial resolution. Based on the proportion of the strain length within the spatial resolution, taking the spectrum of the strain section from the measured spectrum, and fitting the decomposed Brillouin gain spectrum with the Lorentzian curve, the actual strain within a spatial resolution along optical fibers can be obtained. The experimental results demonstrate that this method is applicable to the modification of the measured strain whether its strained length is less or greater than the spatial resolution without considering the installation method of the optical fiber.

Keywords: Brillouin optical time domain reflectometer (BOTDR), spatial resolution, Brillouin gain spectrum, spectral decomposition, Brillouin spectrum width.

1. Introduction

Since it has been found that the power spectrum of Brillouin scattered light changes linearly according to strain [1], measurement instruments using this characteristic for fiber optic sensor system have continuously been produced. One of them is the Brillouin optical time domain reflectometer (BOTDR), a kind of a distributed optical fiber strain sensor, which can measure the longitudinal strain distribution continuously along an optical fiber with high accuracy and high stability [2]. There have been many basic studies on measurement principles and methods to improve the performance of the BOTDR system [3]–[5]. In recent years, great attention has attracted its application in the field of civil engineering and infrastructural systems [6]–[8]. By now, the spatial resolution of BOTDR has reached around 1 m corresponding to 10 ns pulse width or less [9], which meets the measurement needs of strain distribution on common infrastructural systems. However, it is not sufficient for the measurement of some specific local strains, in practice such as the strain caused by narrow cracks or fissures in structures. The direct method to improve the spatial resolution is to narrow the pulse width, meanwhile the accuracy of strain measurement deteriorates abruptly. BROWN *et al.* [10] used a novel signal processing technique to enhance the spatial resolution without decreasing the pulse width. YASUE *et al.* [7] realized a quasi -improvement in the spatial resolution of an optical fiber by forming bends in the optical fiber in the strain generation section. By partially gluing an optical fiber, OHSAKI *et al.* [11] proposed an approximate theoretical equation to enhance the spatial resolution when the strain of the optical fiber is small. In order to improve the spatial resolution, NITTA *et al.* [12] intentionally introduced two kinds of strain within the spatial resolution which results in Brillouin gain spectrum separation.

The methods mentioned above require the particular installation of fiber optic sensors or are used only for certain strain states of the optical fiber, so they are difficult to employ. This paper presents a spectral decomposition method on the basis of the measured spectrums of BOTDR to improve its spatial resolution without narrowing the pulse width. The experiments show that, without considering the installation modes of the optical fiber, the method is effective for improving the measurement accuracy whether the strained length of the fiber is larger or less than the original spatial resolution.

2. Overview of BOTDR

2.1. Measurement principle [13]

A lightwave transmitted through an optical fiber is scattered by nonlinear interaction with acoustic waves, which is called Brillouin scattering. Because the phonons decay exponentially, the Brillouin scattered light spectrum is Lorentzian in form. The frequency at which peak power is obtained in the spectrum is shifted about 11 GHz from the incident lightwave frequency at a wavelength of 1.55 μm. This amount of frequency shift is called a Brillouin frequency shift ν_B. If longitudinal strain ε occurs in the optical fiber, the Brillouin frequency shift ν_B changes in proportion to that strain. The ν_B can be given by the following equation as a function $\nu_B(\varepsilon)$ of the strain ε:

$$\nu_B(\varepsilon) = \nu_B(0) + \left(\frac{\mathrm{d}\nu_B}{\mathrm{d}\varepsilon}\right)\varepsilon \tag{1}$$

where $\nu_B(0)$ is the Brillouin frequency shift without strain, and the proportional coefficient of strain at a wavelength of 1.55 μm is about 0.5 GHz/% (strain).

In fact, the frequency shift of Brillouin scattered light varies in proportion to the fiber's temperature as well as to the strain applied to it. When the changes in temperature are within 2 °C, the effect of the temperature can be neglected.

As shown in Fig. 1, to measure the Brillouin frequency shift with a BOTDR, a pulsed light is launched into one end of an optical fiber and the power of the

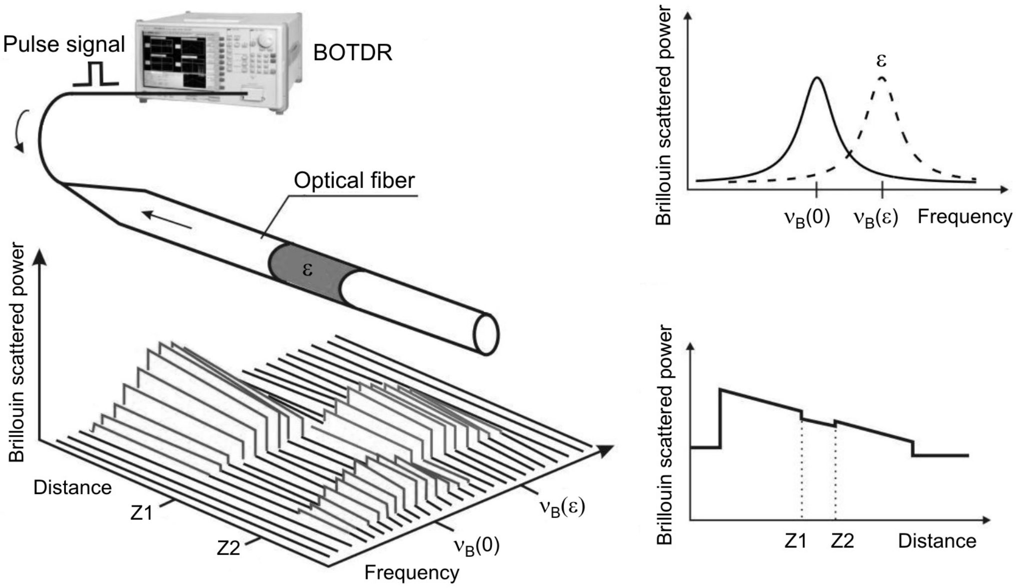

Fig. 1. BOTDR measurement mechanism.

spontaneous Brillouin backscattered light is measured by means of heterodyne detection in the time domain. The frequency of the incident light is changed slightly and the same measurements are made repeatedly at many frequencies to obtain the Brillouin spectrum. The frequency that gives the peak power is calculated by fitting the spectrum to a Lorentzian curve at every point in the optical fiber. The strain is then obtained from that frequency, and the distance of Z from the position where the pulsed light is launched to the position where the scattered light is generated can be determined using the following equation:

$$Z = \frac{cT}{2n}. \tag{2}$$

Here c is the light velocity in a vacuum, n is the refractive index of the optical fiber, and T is the time interval between launching the pulsed light and receiving the scattered light at the end of the optical fiber.

2.2. Spatial resolution

The spatial resolution in these measurements is determined by the pulse width of the incident light. The spatial resolution ΔZ is expressed using a given pulse width τ as

$$\Delta Z = \frac{\nu\tau}{2} \tag{3}$$

where v is the light velocity in the optical fiber. According to Eq. (3), a higher spatial resolution can be obtained by narrowing the pulse width. However, as the pulse width is further narrowed, the line width of the Brillouin gain spectrum becomes wider, and after it exceeds that of the acoustic phonons, the accuracy of the strain measurement deteriorates abruptly. Therefore, the spatial resolution is limited to about 1 m at the present measurement system, which corresponds to 10 ns pulse width.

The spatial resolution determines the ability of BOTDR to locate the strained section and acquire the actual strain distribution along the fiber. If the uniformly strained length of the section along the optical fiber is larger than the spatial resolution, the measurement system can obtain the strain correctly. However, owing to the spatial resolution, the strained length measured by BOTDR is larger than the actual strained length. If the uniformly strained length is less than the spatial resolution, the strain measured by BOTDR is generally smaller than the actual strain. This can be explained as the following Fig. 2. Figure 2 shows a typical Brillouin gain spectrum when a strain is applied to a segment of the optical fiber, in which strained length is less than the spatial resolution. In this figure, spectrum (1) denotes the Brillouin gain spectrum of the unstrained section within the spatial resolution, and spectrum (2) is the Brillouin gain spectrum of the strained section within the spatial resolution. However, the spectrum measured by BOTDR is spectrum (3) which is the superposition of spectrum (1) and spectrum (2). It can be seen that there is a frequency shift between the peak position of the spectrum (3) and that of spectrum (2), which leads to the inaccuracy of the measured strain.

To further verify the above phenomenon, a series of tensile experiments were performed on different lengths of the optical fiber. In the experiments, a pulse width of 10 ns was adopted which corresponds to a spatial resolution of 1 m. The results are shown in Fig. 3. When the tensile length was larger than 1 m, the measured strain had

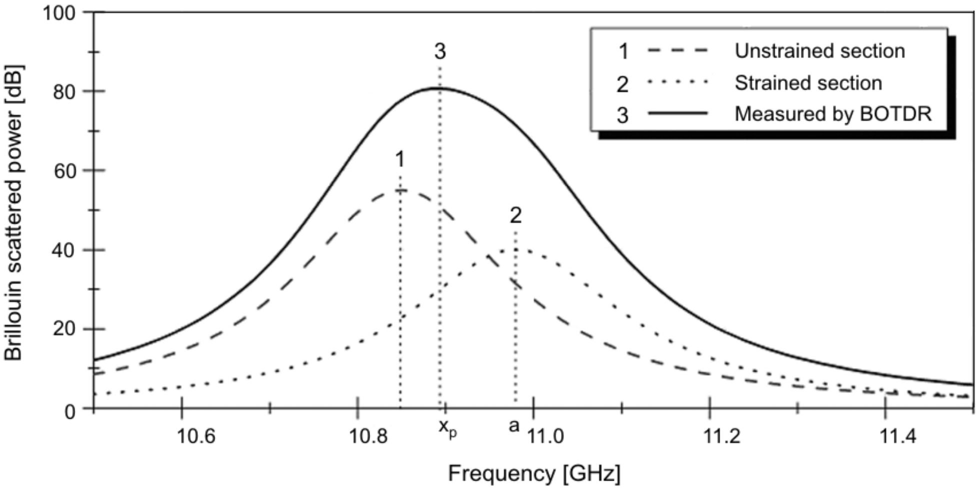

Fig. 2. Brillouin gain spectra when tensile length is less than spatial resolution.

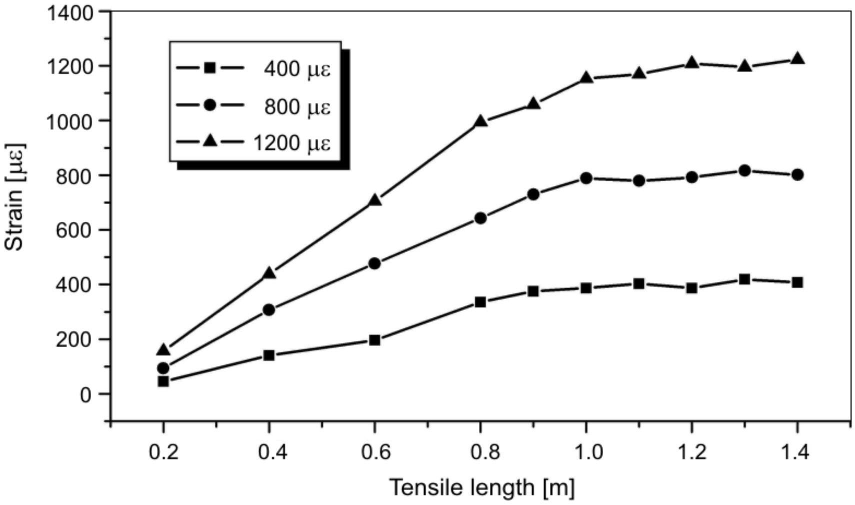

Fig. 3. Relationship between tensile lengths of optical fiber and their measured strains with BOTDR.

a good agreement with the actual strain. However, when the tensile length was less than 1 m, the measured strain decreased in proportion with the ratio of tensile length to the spatial resolution.

Ohsaki *et al.* [11] presented a theoretical analysis of this phenomenon. In their report a simple linear relation of $x_p = ar$ is also given for small strains of less than 1000με, where x_p is the Brillouin frequency shift at the peak position of the compound Brillouin gain spectrum of the measured strain as in spectrum (3) in Fig. 2; a is the Brillouin frequency shift at the peak position of the Brillouin gain spectrum of the actual strain within the spatial resolution in spectrum (2) in Fig. 2, and r ($0 \le r \le 1$) denotes the ratio of strained length to the spatial resolution. Therefore, given r, the Brillouin frequency shift of the strained section can be estimated with the Brillouin frequency shift measured by BOTDR, and the actual strain of the fiber is determined. This equation is very convenient and useful for practical use, however the optical fiber needs to be installed by a specific method. In addition, as an approximate equation, some errors often occur between the calculated strain and the actual strain, especially in the case of large strain of the optical fiber or small r value.

In this paper, a way to find the parameter r from the Brillouin spectrum width is given, and a practical method of spectral decomposition is presented to improve the spatial resolution and to enhance the measurement accuracy of BOTDR without considering the installation of the optical fiber.

3. Spectral decomposition

Since the measured Brillouin gain spectrum is the sum of all components generated in a fiber within the spatial resolution as shown in Fig. 2, herein a method of spectral decomposition on the compound spectrum is proposed to improve the spatial resolution and to obtain the actual strain without narrowing the pulse width.

At first, some functions are defined herein. $P_c(v)$ is the power of the measured compound Brillouin gain spectrum on a length of the optical fiber defined by the spatial resolution within which the optical fiber is partially strained, where v is the sweep frequency; $P_s(v)$ is the power of the Brillouin gain spectrum on a length of the optical fiber defined by the spatial resolution within which the optical fiber is uniformly strained; $P_u(v)$ is the power of the Brillouin gain spectrum on a length of the optical fiber defined by the spatial resolution within which the optical fiber is not strained. $P_c(v)$ can be expressed using the following equation:

$$P_c(v) = P_u(v)(1-r) + P_s(v)r \tag{4}$$

thus,

$$P_s(v) = \frac{P_c(v) - P_u(v)(1-r)}{r}. \tag{5}$$

Theoretically, $P_c(v)$, $P_s(v)$ and $P_u(v)$ all fit a Lorentzian function as follows:

$$g(v) = \frac{(\Delta v_B/2)^2}{(v - v_B)^2 + (\Delta v_B/2)^2}\, g_0 \tag{6}$$

where $g(v)$ is the Brillouin gain spectrum, g_0 is the peak power of the spectrum, Δv_B is the line width of the Brillouin gain spectrum, v_B is the Brillouin frequency shift and v is the frequency of the backscattered light.

The key to this method is to determine the parameter r. HORIGUCHI *et al.* [1] have stated in their report that the Brillouin spectrum width becomes wider when the inhomogeneous strain is applied along the test fiber. Our experiments also confirmed that. It has been found that the Brillouin spectrum width reaches its peak value when the lengths of the strained part and the unstrained part within the spatial resolution are almost the same. Thus, the strained length and position along the optical fiber can be obtained by investigating the Brillouin spectrum width.

As shown in Fig. 4, section *AB* along the optical fiber is uniformly strained. The hollow square line indicates a typical Brillouin spectrum width of the sampling points. The sampling range (the same as the spatial resolution) and the value of r at each sampling point are illustrated in Fig. 4. When the length of the strained section equals the length of the unstrained section within the spatial resolution, *i.e.*, $r = 0.5$, the Brillouin spectrum width reaches its peak, as the sampling points e and j in Fig. 4, which just corresponds to both ends of the strained section *AB*. Therefore, the length of the uniformly strained section and its position along the optical fiber can be determined by picking the peaks of the Brillouin spectrum width. Then the value of r at each sampling point that contains a certain length of the strained section within its spatial resolution can also be determined. With the parameter r, $P_s(v)$ can be obtained

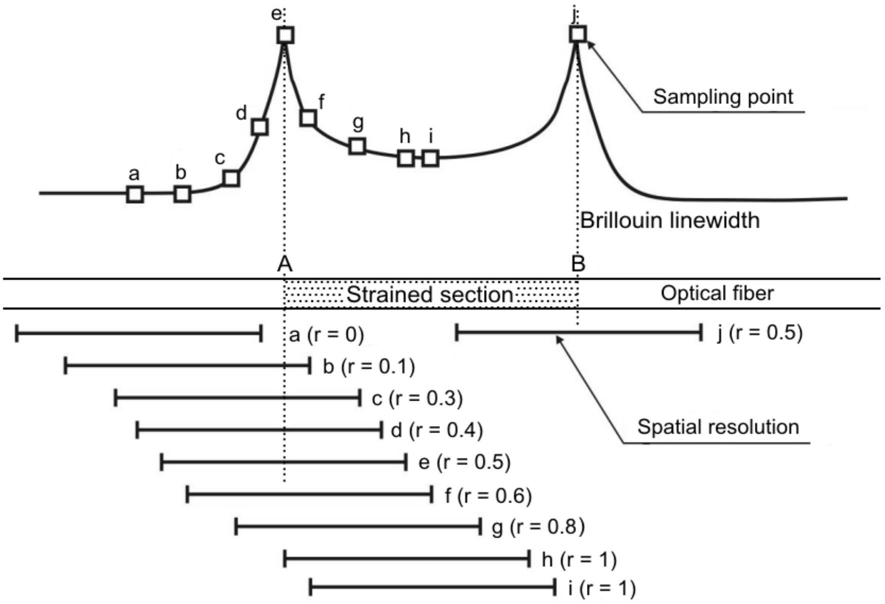

Fig. 4. Distribution of *r* along the partially strained optical fiber.

through Eq. (5), then the Brillouin frequency shift $v_B(\varepsilon)$ is obtained by fitting $P_s(v)$ with Lorentzian curve, and the actual strain ε within the spatial resolution is calculated with Eq. (1).

If the optical fiber is non-uniformly strained, the strained fiber can be divided into some sections within which the strain distribution is considered to be uniform.

4. Experimental verification

4.1. Tensile length is larger than the spatial resolution

In order to verify the feasibility of the above-mentioned method, several experiments were done. For the case that the tensile length of the optical fiber is larger than the spatial resolution, 1.2 m length of the optical fiber was taken to tension and a 1000με strain was generated on it. The pulse width of BOTDR was set to 10 ns, and the corresponding spatial resolution was 1 m. Figure 5**a** shows the measured strain distribution. As the tensile length of the optical fiber is larger than the spatial resolution, the actual strain of the strained section was measured by reading the peak value at the sampling point *h*. However, as to the sampling points *c*, *d*, *e* and *f*, the measured strain is different from the actual strain because the fiber is partially strained within the spatial resolution. If the value of *r* at those sampling points is determined, the actual strain at sampling point *c* to *f* can also be calculated by analyzing their Brillouin gain spectra.

Figure 5**b** shows the Brillouin spectrum width along the optical fiber. As stated above, the actual length of the strained section is acquired by picking the distance

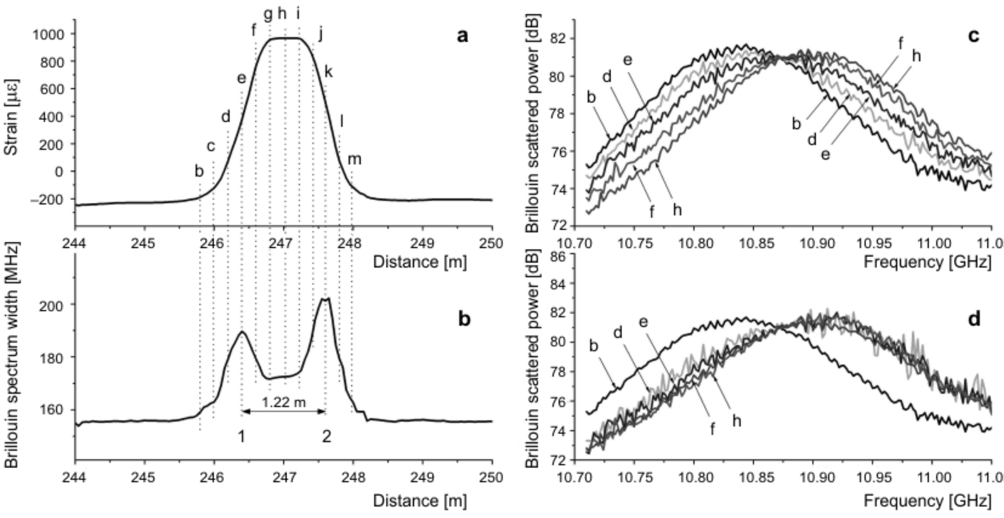

Fig. 5. Illustrations of the spectral decomposition.

between the peaks 1 and 2. The measured distance between points 1 and 2 is 1.22 m, which is almost equal to 1.2 m of the actual length. Thus, the value of *r* at each sampling point can be determined by the use of the method introduced above in this paper.

Figure 5**c** is the measured Brillouin gain spectra at different sampling points. The labels of *b* to *h* in Fig. 5**c** are corresponding to those in Fig. 5**a**. Spectrum *b* is the measured Brillouin gain spectrum when the optical fiber is not strained ($r = 0$). Spectrum *h* is the Brillouin gain spectrum measured when the optical fiber within the spatial resolution is uniformly strained ($r = 1$). Spectra *d*, *e* and *f* are the Brillouin gain spectra measured when the optical fiber within the spatial resolution is partially strained ($0 < r < 1$). It can be seen that the Brillouin frequency shifts of spectra *d*, *e* and *f* are all less than that of the spectrum *h*. Therefore, the strains obtained by fitting these measured spectra do not agree with the actual strains of the optical fiber. The value of *r* of the spectra *d*, *e* and *f* are 0.3, 0.5 and 0.7, respectively, which indicates that the proportions of the strained section within the spatial resolution are 30%, 50% and 70%. When the value of *r* gets close to 1, the measured strain is near to the actual strain of the optical fiber. The modified Brillouin gain spectra at some sampling points obtained through the spectral decomposition are shown in Fig. 5**d**. Spectrum *h* is the Brillouin gain spectrum when the spatial resolution is fully strained, and spectra *d*, *e* and *f* are the modified Brillouin gain spectra of the strained section within the spatial resolution, respectively, which have a good agreement with spectrum *h*, and their calculated strains are almost the same as the actual strains.

Figure 6 shows the measured strain distribution and the calculated strain distribution by the use of the spectral decomposition. The calculated strains at sampling point *c* to *m* fluctuate around 1000 με, and their average value is 1023 με which equals the actual strain approximately.

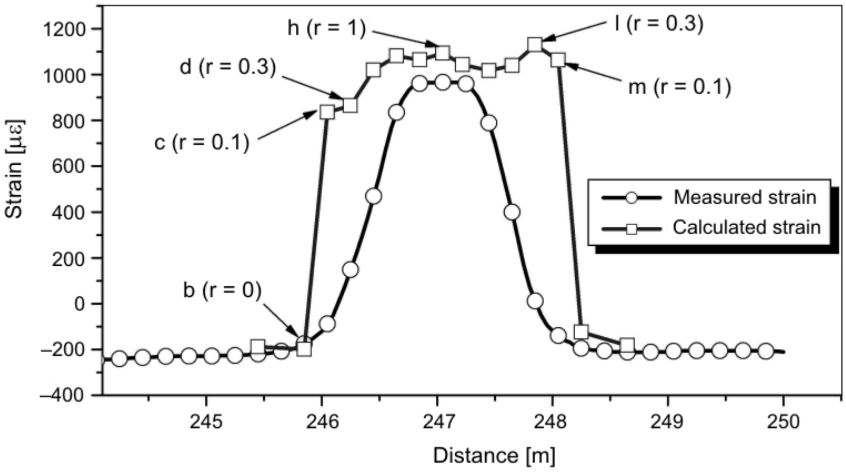

Fig. 6. Measured strain by BOTDR and the calculated strain by the decomposed Brillouin spectrum.

In addition, the experiments also show that the strains calculated by the use of spectral decomposition have a good agreement with the actual strains when *r* is larger than 0.5. Otherwise the error occurs when *r* is less than 0.5 (see the sampling points *c*, *d*, *l* and *m*) because the spectrum of the strained section has little contribution to the measured Brillouin gain spectrum, which leads to the roughness of the decomposed Brillouin spectrum.

4.2. Tensile length is less than the spatial resolution

For the case that the tensile length of the optical fiber is less than the spatial resolution, another tensile experiment was performed. A 1.2 m length of the optical fiber was taken to tension and a 1000 με strain was generated on it. The pulse width of BOTDR was set to 20 ns, and the corresponding spatial resolution was 2 m.

The experimental results are shown in Figs. 7 and 8. In Fig. 7**a**, it can be found that the strain of the peak point *k* is about 700 με, less than the actual strain of 1000 με. The tensile length and position can also be obtained by picking the peaks of the Brillouin spectrum width shown in Fig. 7**b**, although the peaks are not as distinct as shown in Fig. 5**b**. The calculated tensile length is 1.22 m, which has a good agreement with the actual length 1.2 m. And then, the value of *r* at each sampling point around the strained section is determined by the use of the method shown in Fig. 4. Figure 7**c** shows the measured Brillouin gain spectra at some sampling points. Spectrum *b* is the Brillouin gain spectrum of the unstrained optical fiber and spectra *f*, *h* and *k* are the Brillouin gain spectrums when the optical fiber within spatial resolution is partially strained. The decomposed Brillouin gain spectra at sampling points *f*, *h* and *k* are shown in Fig. 7**d**, which have all good agreement with the Brillouin gain spectrum of fully strained optical fiber within spatial resolution. Thus, the actual strain of the optical fiber is obtained.

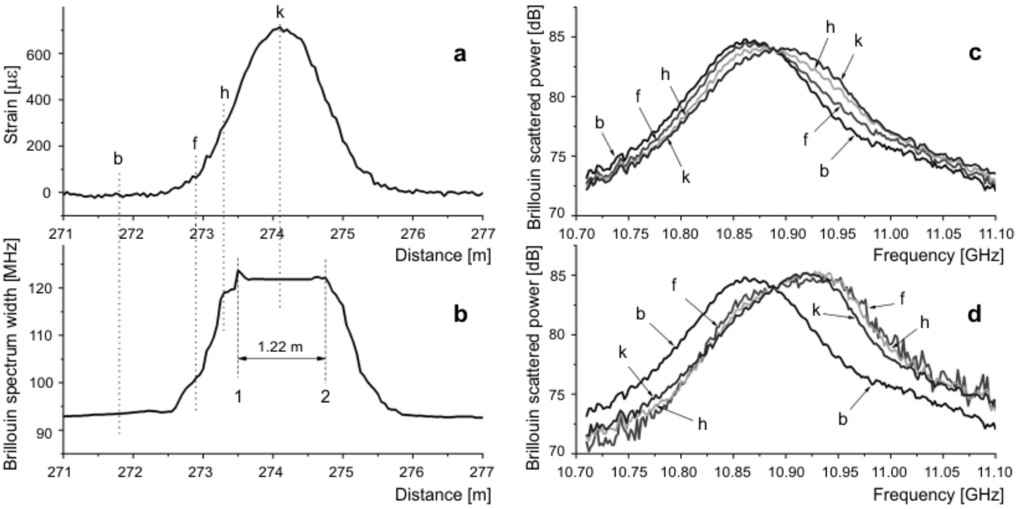

Fig. 7. Illustrations of the spectral decomposition.

The comparison of the measured strain by BOTDR with the calculated strain by the spectral decomposition is shown in Fig. 8. The calculated strain is closer to the actual strain than the measured strain. The average value of the decomposed strain is about 951 με, which approximates to the actual strain 1000 με. Therefore, by the use of spectral decomposition, the spatial resolution of BOTDR is improved; on the other hand, more accurate strain distribution can be obtained, especially when the tensile length is less than the spatial resolution.

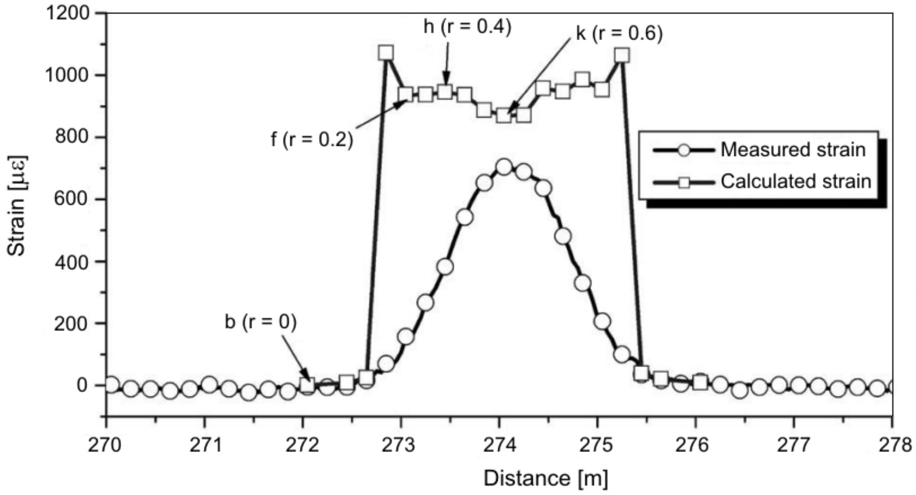

Fig. 8. Measured strain by BOTDR and calculated strain by decomposed Brillouin spectrum.

5. Conclusions

In this paper, a spectral decomposition method is proposed to improve the spatial resolution of BOTDR, as well as the measurement accuracy of strain distribution without narrowing the pulse width. The length of the strained section along the optical fiber is obtained by picking the peaks of the Brillouin spectrum width. The actual strain distribution of the optical fiber is obtained by the use of the spectral decomposition method. The experiments have verified that this method is applicable to improving spatial resolution and enhancing accuracy of strain measurement whether the strained length is less or larger than the spatial resolution without considering the installation method of the optical fiber.

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