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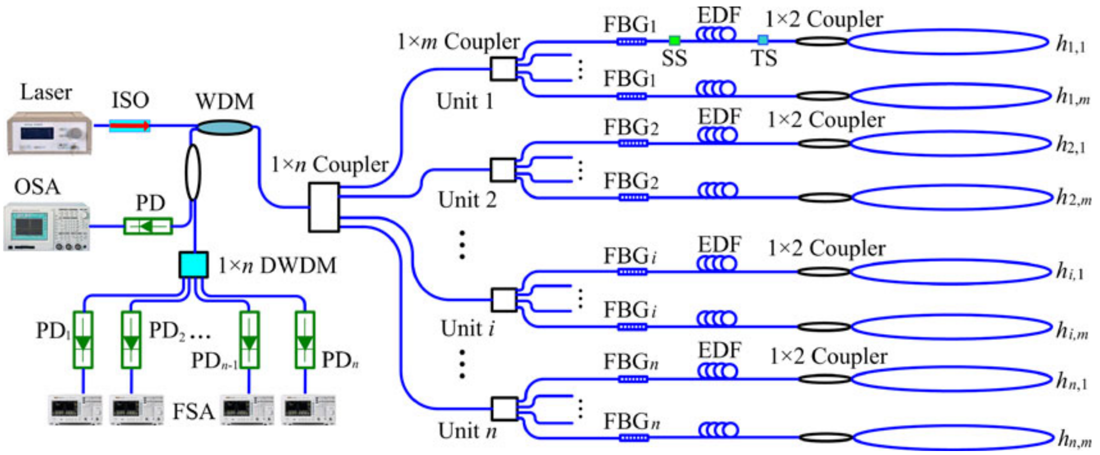

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Real-Time Interrogation Technology for a Large-Scale Fiber-Ring Laser Sensor Array

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Abstract: A real-time interrogation technology for a large-scale fiber laser sensor array is proposed and experimentally investigated by employing a hybrid topological structure based on the wavelength- and frequency-division multiplexing techniques. In this system, a 2-D $n \times m$ sensor array is established by using a $1 \times n$ coupler and n $1 \times m$ couplers. All sensors are divided into n units by the $1 \times n$ coupler. In each unit, there are m fiber-ring laser sensors with approximately the same wavelength and different beat frequencies due to different laser cavity lengths. Meanwhile, different units are characteristic of different operating wavelengths by splicing different fiber Bragg grating (FBG) as a reflector. Therefore, each sensor has a unique wavelength- and frequency-encoded information. All sensors can be interrogated by the combination of wavelength and frequency multiplexing technology. In the paper, a 4×4 sensor array is set up experimentally to verify the interrogation ability, and the sensing information of the strain and temperature has been successfully extracted. The experimental results show that the proposed interrogation system has the ability of real-time monitoring for a large-scale fiber laser sensor array.

Index Terms: Fiber laser sensor, beat frequency, interrogation technology, frequency/wavelength division multiplexing.

1. Introduction

Fiber laser sensors not only possess many advantages of fiber Bragg grating (FBG) sensor, for example, compact size, light weight, and immunity to electromagnetic interference, but also have higher sensitivity and precision than FBG sensors [1], [2]. Thus, they have been used extensively to measure many parameters, such as strain, temperature, vibration and pressure acceleration [3], [4]. In addition, the fiber sensor has the ability to form large-scale sensor networks for monitoring large-scale infrastructure construction, and acoustic filed [5]–[7]. Generally, the elaborate interferometric demodulation device was used to transform wavelength information into phase information. The interferometric signal suffers easily from various disturbances, which degrades the signal-noise

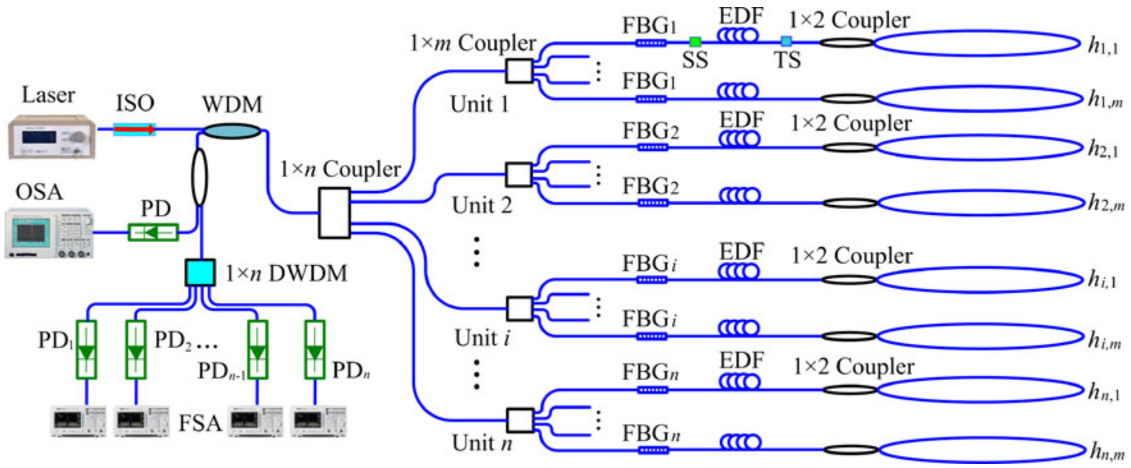


Fig. 1. Scheme configuration of the $n \times m$ MMERL sensor array. (FBG: fiber Bragg grating; WDM: wavelength division multiplexer; FSA: frequency spectrum analyzer; OSA: optical spectrum analyzers; PD: photodetector; ISO: isolator; Laser: 1480 nm pump laser; DWDM: dense wavelength division multiplexing).

ratio (SNR) and stability of the sensor. The beat frequency interrogation technology successfully avoids these problems, because the sensing information of the beat signals are frequency-encoded information, which is not the wavelength or phase information [8]. Since the frequency information is immune to the perturbation of the light power and light polarization, the beat frequency interrogation technology improves the SNR and stabilization of the sensor system. Meanwhile, the beat frequency demodulation system needs only a photodetector and a frequency analyzer (FSA), instead of the complicated optical interferometric demodulation device. It reduces the complexity of the demodulation devices. These attractive advantages make the beat frequency interrogation technique have been widely applied to measure stress, temperature, acoustic, vibration, and other sensing fields [9]–[12].

The same as the ordinary fiber laser sensors, the fiber laser sensor based on the beat frequency interrogation technology has the potential multiplexing ability for a large-scale array. In order to interrogate more sensors, several kinds of interrogating technologies were developed, such as the polarimetric heterodyning technology [13], wavelength division multiplexing (WDM) technology [14], and frequency division multiplexing (FDM) technology [15], [16]. In these technologies, the polarimetric heterodyning technology and the WDM interrogation technology depend on the wavelength of laser sensor, and the FDM technology depends on the cavity length of laser sensor. Since two interrogation technologies allow to address multiple sensors by two different characteristic parameters, the combination of WDM and FDM will be able to synchronously interrogate larger number of fiber laser sensors than any one WDM or FDM technology. This hybrid multiplexing technology is expected to greatly reduce the cost and the complexity of the sensor system. It will inevitably promote the application of the laser sensors in large-scale measurement system.

In this article, the real-time interrogation technology for large-scale multilongitudinal mode fiber-ring laser (MMFRL) sensor array is proposed. The sensors are interrogated by the combination of the WDM and FDM technologies. The proposed method simplifies the complexity of the system using some simple WDM and FDM demodulation devices.

2. Principle

The scheme configuration of the proposed $n \times m$ elements MMFRL sensor array system is shown in Fig. 1. The $n \times m$ topological array is constructed by a $1 \times n$ coupler and n $1 \times m$ couplers. The 1480 nm pump light source passing through an optical isolator (ISO) and a 1480 nm/1550 nm wavelength division multiplexer is launched into each fiber laser sensor through $1 \times n$ coupler and 1 × m coupler in turn. Each MMFRL cavity is consisted of a fiber Bragg grating, a piece of Erbium-doped-fiber (EDF), and a 1 × 2 coupler (3 dB). The two output ports of the coupler are spliced together to form a fiber ring laser cavity. In the proposed sensor array, 1 × n coupler divides all fiber sensors into n units. For each unit, there are m MMFRL sensors with the same wavelength and different cavity lengths. According to the principle of laser, they have different beat frequencies [15]. So the m fiber-ring lasers in each unit can be interrogated by the FDM technology. For different units, the fiber laser sensors are characteristic of different operating wavelengths by using different wavelength FBGs as reflecting mirror of fiber laser cavity. In other words, in one unit, the wavelengths of all fiber lasers are almost equal. All optical signals of each unit, which includes m MMFRL sensors information, can be guided into the designed channel by the dense wavelength-division multiplexer (DWDM) according to the operating wavelength. And then, all beat signals in each unit are converted into electrical signals on the PD and discriminated by FDM technology using a FSA. The beat frequency shift of the MMFRL sensor can be measured by the FSA. Therefore, the proposed sensor system is capable of real-time monitoring for the each sensor in a large-scale sensors array using FSA by combining FDM and WDM techniques.

According to the principle of laser, the frequency interval between two adjacent longitudinal modes in one laser cavity can be expressed as [17]

$$f = \frac{c}{Ln_{\mathrm{eff}}} \tag{1}$$

where c is the light velocity in vacuum, L is the effective cavity length of MMFRL, and n_{eff} is the effective refractive index. f is also the resonant frequency of the laser cavity. All frequencies of beat signals of $h_{i,j}$ sensor element are expressed as

$$f_{i,j}^{K} = \frac{kc}{L_{i,j} n_{\mathrm{eff}}} = k f_{i,j}^{1}, (i = 1, 2, \ldots.n,\ j = 1, 2, \ldots.m) \tag{2}$$

where k is the order number of the beat frequency, i is the i-th unit in the array, and its number is the channel number of the 1 × n coupler. j is the j-th sensor in the i-th unit. $h_{i,j}$ sensor is j-th sensor in i-th unit. $f_{i,j}^{1}$ is the 1st order beat frequency of the $h_{i,j}$ MMFRL sensor, namely, it is the resonant frequency of the laser $h_{i,j}$. It is obvious that the beat frequencies of each sensor in each unit are different, if the cavity lengths of the fiber lasers are different.

When the ring cavity is stretched by the applied strain or suffers from the temperature change, the effective refractive index and the length of the MMFRL cavity will also change [16]–[18]. Therefore the frequency of beat frequency will shift, and it can be expressed as

$$\delta f_{i,j} = -f_{i,j} \frac{L'_{i,j}}{L_{i,j}} [(1 - P_{\mathrm{e}})\varepsilon + (\xi + \alpha)\Delta T] \tag{3}$$

where $L'_{i,j}$ is the effective sensing length of the laser sensor in the sensing zone, and $L_{i,j}$ is the total cavity length. ΔT is the temperature change, ξ and α are the thermo-optic and the thermal expansion coefficients of the fiber, P_{e} is the photo-elastic constant, and $P_{\mathrm{e}} = 0.22$. ε is the strain applied on the sensor. The applied strain or temperature changes will be obtained by measuring the frequency shift of the beat signal.

In the same unit, the frequency is designed deliberately by fabricating the cavity lengths carefully, and let them meet the following expression, which is

$$f_{i,j}^{1} = f_{i,1}^{1} + (j - 1)\Delta f \tag{4}$$

where j is j-th sensor in i-th unit, and Δf is the frequency interval of the first order frequency for any two adjacent laser sensors. Though careful design on the cavity length of the laser sensor, we can make the adjacent lasers have the same frequency interval.

In one unit, there are some potential crosstalks among different sensors. Take unit 2 as an example, the beat frequency signals are shown in Fig. 2. $f_{2,j}^{k}$ is the k-th order BFS of the j-th sensor in the unit 2. The frequency interval of the two adjacent laser sensors on the k-th order is $k\Delta f$. When $f < f_{2,m}^{k}$, all beat signals do not overlap and each sensor can be distinguished synchronously based

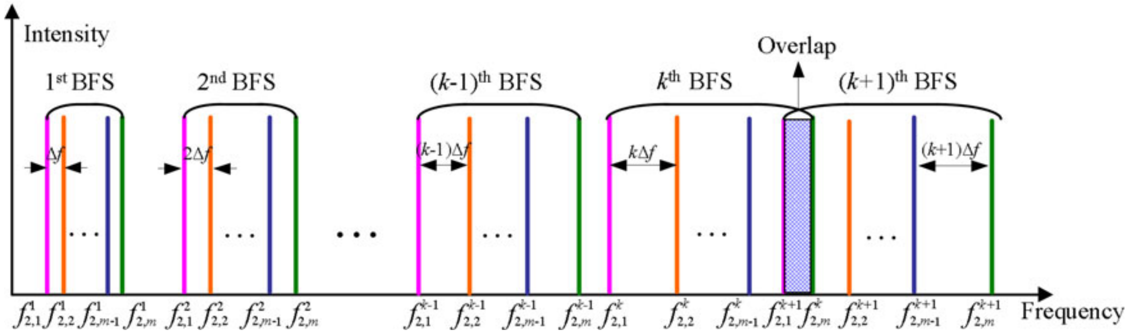


Fig. 2. Beat frequency signals (BFSs) of the unit 2 of the FDM-MMFRL sensing system.

on its frequency range. As the frequency increases with the order of beat signals, the $(k+1)$-th beat signal and k-th beat signal will overlap, the beat signals will can not be distinguished by FDM.

According to what has been discussed above, the maximum number of the sensor in one unit can be shown on [16]

$$G_{\max} = \frac{f_{i,1}^{1}}{f_{\max}(1-P_{\mathrm{e}})\varepsilon_{\max}} + 1 \tag{5}$$

where $f_{\max}$ is the maximum detectable frequency, and $\varepsilon_{\max}$ is the maximum strain that the fiber can be loaded. The maximum multiplexing number in the i-th unit depends the maximum strain applied on the fiber, the first order beat frequency $f_{i,1}^{1}$ in one i-th unit and the maximum detectable frequency. These parameters can be optionally designed in this system, so this system shows the great flexibility in various application fields. When the frequency of the beat signal is less than $f_{\max}$, all beat signals can be interrogated without any overlapping.

3. Experiments and Results

To verify the proposed multiplexed MMFRL sensor array, a 4 × 4 MMFRL sensor array was established by carefully designing the parameters of the fiber-ring laser, including the cavity length and operating wavelength of the fiber laser. The 1480 nm pump laser is divided into four parts by one 1 × 4 coupler, and then launched into each sensor to illuminate each MMFRL through another 1 × 4 coupler. So, there are 16 MMFRL sensors in the array. The wavelengths of all FBGs in each unit are the same as each other. The reflectivity and bandwidth of all FBGs are also the same, which are about 90% and 0.20 nm, respectively. The operating wavelengths of the four units λ_{FBG1}, λ_{FBG2}, λ_{FBG3}, λ_{FBG4} are about 1546.12 nm, 1547.72 nm, 1549.32 nm, and 1550.92 nm, respectively. A section of EDF is used to serve as gain medium in each laser cavity, whose length is about 1.20 m, and its absorption is 37.2 dB/m @ 1531 nm. The cavity lengths and corresponding first order frequency of the beat signal of the 16 lasers are shown in Table 1. For any two adjacent lasers in each channel, the frequency separation of the first order beat signal is about 0.20 MHz, which means $\Delta f = 0.20$ MHz.

In the experiment, the dense wavelength-division multiplexer (DWDM) divides the optical signals of different units into different channels. Generally, the DWDM has five bands, which is O, E, S, C and L band. The gain spectrum of the Er^{3+} fiber is just in the C-band. In this experiment, according to different operating wavelengths of four units, a 1 × 4 DWDM with C33, C35, C37, and C39 is used to divide the sensing signal into four channels.

When the pump power is higher than 213.0 mW, the 16 MMFRLs are stimulated stably. Fig. 3 shows the optical spectra of the MMFRLs sensor array. There are four parts. The center wavelengths of each part are 1546.12 nm, 1547.72 nm, 1549.32 nm, and 1550.92 nm, respectively. They are just the operating wavelengths of the each unit in the sensor array. For each wavelength,

TABLE 1
Parameters of Cavity Length and First-Order Beat Frequency

Unit	Wavelength (nm)	Sensors	Cavity length(m)	Frequency (MHz)
Unit 1	1546.12	$h_{1,1}$	5.640	36.20
	1546.12	$h_{1,2}$	5.578	36.40
	1546.12	$h_{1,3}$	5.560	36.60
	1546.12	$h_{1,4}$	5.540	36.80
Unit 2	1547.72	$h_{2,1}$	5.639	36.21
	1547.72	$h_{2,2}$	5.578	36.39
	1547.72	$h_{2,3}$	5.559	36.60
	1547.72	$h_{2,4}$	5.538	36.81
Unit 3	1549.32	$h_{3,1}$	5.641	36.20
	1549.32	$h_{3,2}$	5.579	36.39
	1549.32	$h_{3,3}$	5.562	36.59
	1549.32	$h_{3,4}$	5.537	36.83
Unit 4	1550.92	$h_{4,1}$	5.639	36.19
	1550.92	$h_{4,2}$	5.581	36.37
	1550.92	$h_{4,3}$	5.563	36.56
	1550.92	$h_{4,4}$	5.536	36.83

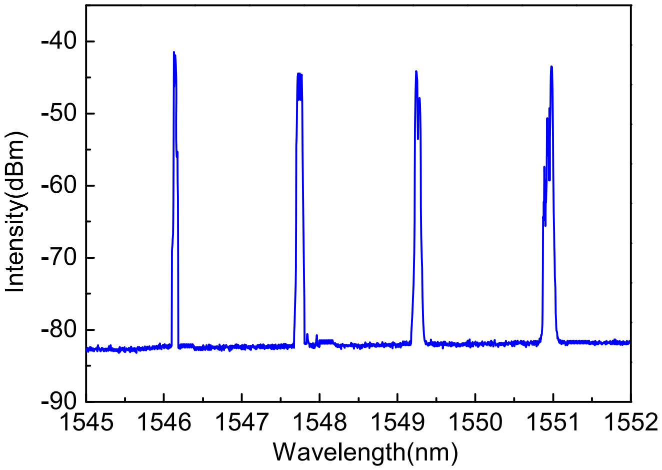
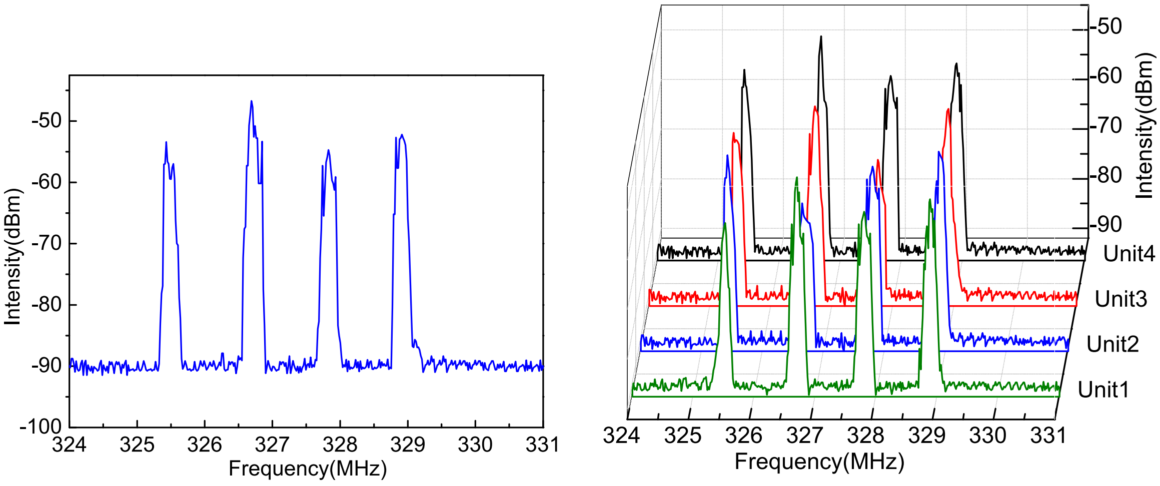


Fig. 3. Optimal spectrum of the 4 × 4 MMFRL sensor array.

because of four MMFRLs with approximate identical wavelengths, all spectra of MMFRLs in each unit simply overlay together. It is clear that the optical signals of four MMFRL sensors in one unit could not be interrogated by an optical spectrum analyzer.

Fig. 4(a) shows all frequency spectrum of 4 × 4 sensor array before through the DWDM. There are only four frequency spectra but not sixteen frequency spectra. It is coincident with the design of experiments as shown in Table 1. Obviously, it also can not interrogate all sensing information by only FDM. Fig. 4(b) shows the frequency spectrum of 4 × 4 sensor array after through the DWDM.



(a)

(b)

Fig. 4. (a) Frequency spectrum of 4 × 4 sensor array before through DWDM. (b) Frequency spectrum of 4 × 4 sensor array after through DWDM.

The four curves are corresponding to the frequency spectrum of four units which come from four channels of the DWDM, respectively. By combining wavelength and frequency information, the sensing signal of each sensor has a unique identification. The sensing signals of each sensor can be interrogated by the hybrid FDM and WDM technology. In the experiment, the SNR of each laser is over 30 dB. Meanwhile, the SNR will decrease with the increase of the detected frequency order. According to Eq. (3), the higher beat frequency has higher strain and temperature sensitivities. So it should be traded off between the SNR and the sensitivity when choosing the sensing frequency.

In this experiment, for each unit, the minimum frequency of beat signal is about 36.20 MHz, Assuming $f_{\max}$ is 905 MHz, $\varepsilon_{\max}$ is 5000 $\mu\varepsilon$. According to (5), the maximum of the frequency multiplexed sensors is 11. For the current commercial DWDM product, it can multiplex up to 25 channels with wavelengths spacing of 1.6 nm in the C-band. So the proposed multiplexing technology can address up to about 275 fiber laser sensors.

To investigate the potential strain applications of the proposed sensor array, strain experiment was carried out using $h_{1,1}$ sensor. A piece of EDF with the length of 1.00 m, which located in between the FBG and the fiber ring, was stretched for applying axial strain by the stationary stage (SS) and translation stage (TS), as shown in Fig. 1. The temperature was kept constant during this measurement. The beat frequency signals located at 325.58 MHz and 760.02 MHz are chosen as the detecting frequencies. When the strain is increased from 0 $\mu\varepsilon$ to 3000 $\mu\varepsilon$, the response of the beat frequency to strain is shown in Fig. 5. The beat signal frequencies decreased as the strain increasing. It is consistent with the theoretical value of (3). The strain sensitivities of the beat frequencies are -0.0889 kHz/$\mu\varepsilon$@325.58 MHz and -0.222 kHz/$\mu\varepsilon$ @760.02 MHz, respectively. The coefficients of linear correlation are both 0.998. The root mean square (RMS) of the strain experiment data is 0.8 kHz@760.02 MHz, and the corresponding minimum resolvable strain is about 3.6 $\mu\varepsilon$.

Another potential application of temperature measurement was verified by another laser sensor. The $h_{2,2}$ sensor was used for temperature measurement. The sensor was placed into a temperature chamber. When the temperature is increased from 0 °C to 60 °C, the relationship of the beat frequency and the temperature are plotted in Fig. 6. The temperature sensitivities are -2.39 kHz/°C@315.60 MHz and -4.90 kHz/°C@687.10 MHz, and the coefficients of linear correlation are 0.9991 and 0.997, respectively. The root mean square (RMS) of the temperature experiment data is 1.5 kHz @687.10 MHz, and the corresponding minimum resolvable temperature is about 0.31 °C. In addition, we have also tested the stability of the fiber laser sensor. In the stability

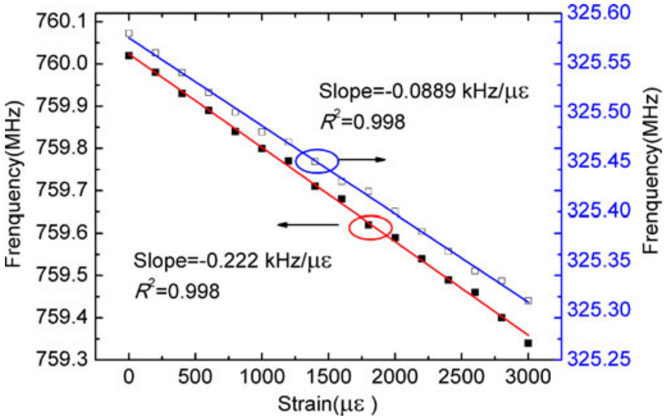


Fig. 5. Strain response of the beat signals of $h_{1,1}$ sensor.

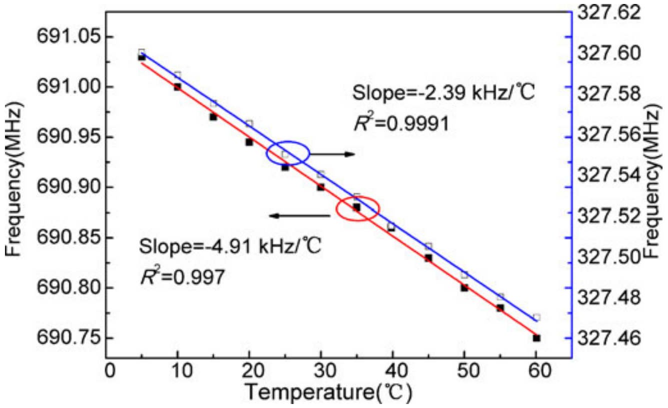


Fig. 6. Temperature response of the beat signals of $h_{2,2}$ sensor.

test, the laser was directly placed in the lab without applied strain and the temperature was kept at room temperature. The frequency fluctuation of the fiber laser sensor is about ± 0.78 kHz within 60 min, which correspond to the strain accuracy of ±3.5 $\mu\varepsilon$ and the temperature accuracy of 0.2 °C.

In the proposed WDM/FDM multiplexing system, the potential crosstalk between the adjacent sensors and adjacent units should also be considered. The crosstalk from the adjacent sensors can be avoided by careful design of the multiplexing system parameters according to (3). Another potential crosstalk of adjacent units is originated from the wavelength overlapping of two adjacent units. Due to the wavelength shift of FBG induced by temperature change, the fiber laser operating wavelength is affected by the temperature change. The temperature sensitivity of FBG wavelength is 10.2 pm/ °C. The environmental temperature range is usually from –20 °C to 80 °C. In this case, the operating wavelength change induced by temperature variation is about 1.02 nm. It is smaller than the channel spacing of 1.6 nm for the used DWDM. Therefore, the crosstalk caused by the environment temperature perturbation will not occur. The proposed hybrid system has the advantage of very low crosstalk between the adjacent sensors and adjacent units.

In addition, the cross-sensitivity about the strain and temperature is a very important issue in fiber, and some methods for solving the cross-sensitivity have been proposed [19]–[22]. In the multi-longitudinal mode fiber sensor, there are two types of beat signals, including polarization beat signal by beating two orthogonality polarization modes and longitudinal beat signal by beating two longitudinal modes at same direction. They have different responses to temperature and strain, so the sensor has the ability to measure the temperature and strain by the matrix in [23].

4. Conclusion

In summary, a real-time interrogation technique for MMFRL sensor array is proposed by combining the FDM and WDM technologies. The large-scale MMFRLs sensor array has been developed and experimentally investigated. This hybrid multiplexing system consists of many units. In each unit, all MMFRL sensors are characteristic of equal operating wavelength and different resonant frequencies, which can be interrogated by the FDM technology. Different units are characteristic of different operating wavelengths, and they are discriminated by a commercial DWDM. Finally, all sensors can be real-time interrogated by the combination of frequency and wavelength multiplexing technology.

To verify the interrogation ability of the proposed system, a 4×4 sensor array is established and the measurement of temperature and strain are demonstrated experimentally. The experimental results show that the proposed multiplexing system can real-time interrogate large-scale MMFRL sensor array. In addition, some potential crosstalks in the proposed sensor array are discussed in detail. Theoretically, the multiplexing system can address up to 275 fiber laser sensors. The proposed multiplexing system can greatly increase the multiplexing number and reduce the weight, volume, and cost of the fiber laser sensors system. Meanwhile, the proposed system also shows great flexibility for the sensor parameters based on the application field. The hybrid multiplexing system is very competitive in some applications fields requiring large scale arrays such as civil, marine infrastructure systems, space vehicles, and so on.

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