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Integrated real-time monitoring system for strain/temperature distribution based on simultaneous wavelength and time division multiplexing technique

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ABSTRACT

Based on the combination of wavelength- and time-division multiplexing technique, a novel fiber Bragg grating (FBG) sensor multiplexing system is proposed, which can be used for monitoring the two-dimensional strain and temperature field distribution in large structures. The FBG sensing unit is encoded simultaneously in both wavelength and time domains. Using the semiconductor optical amplifier (SOA) resonant cavity technology, a large capacity multiplexing technology with mixed time-division and wave-division multiplexing (TDM+WDM) is presented. The sensor array contains many groups with each group composed of many sensors. The group is addressed by TDM mode and each sensor of the groups is accessed by WDM mode. Therefore, the total multiplexing capacity is multiplication of TDM and WDM. In theory, more than 1000 sensors can be multiplexed on one single fiber. The feasibility of the scheme was experimentally demonstrated through a sensor system with a two dimensional FBG sensing network with 5×5 sensors arrays. In addition, the strain/temperature distribution in an aluminum plate was measured at real time under different loading/heating by using above FBG sensing network.

1. Introduction

The goal of structural health monitoring is to achieve real-time monitoring and prediction for the overall behavior of the structure. The monitoring system should have ability to deal with crossed duties for accomplishing the large-capacity and fast data collection, transmission, processing and analysis in real time. In actual project application, whole field measurement (e.g. temperature field or strain distribution) is necessary for the proper monitoring of large structures. Many strain/temperature measurements typically use external electrical strain gages /thermo-meter. Most of them are limited by response time, multiplexing potential, long term durability, temperature range and susceptibility to electromagnetic interference for real-time strain and temperature monitoring. Fiber grating sensor [1] has the potential to overcome all these issues. Over the past two decades, as an important part of the optical fiber sensor, fiber Bragg grating sensors [2] have attracted a lot of attentions due to their small size, light weight, immunity to electromagnetic interference, high sensitivity, ease of fabrication, location, intrinsic nature, wavelength encoded operation, low cost system and flexible multiplexing ability. In consideration of the requirements (numerous points' strain and temperature) of the structural health monitoring, FBG sensors are quite for the large structure's health monitoring. FBG sensors have been developed from the laboratory to the practical application [3], such as aerospace, petroleum chemical industry and the civil engineering areas.

Many researchers have investigated how to monitor the structural strain/temperature field distribution using fiber sensors network. Berkoff et al. proposed the wavelength division multiplexing (WDM) technique for numerous points' measurement [4]. Dai et al. investigated the time division multiplexing (TDM) technique for enlarge the capacity of one single fiber [5]. However, the maximum multiplexing sensors numbers of WDM and TDM system are limited by the width of broadband source and the reflectivity of sensor respectively. Rao et al. combined the (space division multiplexing) SDM, WDM and TDM to realized large capacity measurement in theory [6]. Li et al. have demonstrated the novel FP fiber sensor system for temperature distributed measurement [7].

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Many works have been done using TDM and WDM multiplexing technology. Most researchers focus on the fabrication of the novel sensor unit or the multiplexing technology with complex configuration, less work has been done on the integrated monitoring system with simple configuration and easy to use. In this paper, we proposed an integrated real-time monitoring system for strain/temperature distribution using FBG sensors arrays. With the WDM+TDM scheme, the monitoring system has the potential to multiplex over 1000 FBGs on a single fiber. Quasi-distributed measurement of the strain/temperature field of an aluminum plate is demonstrated experimentally, with the real-time data display.

2. Operation principle and manufacturing

2.1. Manufacturing of sensing units

The FBG sensors were UV inscribed in hydrogen loaded standard fiber (SM-28) using a frequency doubled Ar ion laser with the standard phase mask scanning technique. Five groups wavelength (1546 nm, 1548 nm, 1550 nm, 1552 nm and 1554 nm) FBGs with 1 mm grating length were fabricated. The short length grating was chosen to avoid spectrum splitting caused by uniform stress. After UV inscription, the FBGs were annealed at 80 °C for 48 h to stabilize their property at high working temperatures. Finally, in order to maintain the durability, the stripped grating area was recoated using an acrylic resin.

2.2. Sensing principle

The principle of operation commonly used in a FBG based sensor system is to monitor the shift in wavelength of the returned "Bragg" signal due to external perturbances [8]. The wavelength of the FBG changes with strain and temperature as Eq. (1)

$$\frac{\Delta\lambda}{\lambda_0} = K\varepsilon + \alpha_\delta \Delta T \tag{1}$$

If a mechanical strain is applied to the grating, the grating period changes and a shift in the reflected Bragg wavelength can be detected. The shift in Bragg wavelength with $\Delta\lambda_B$ strain ε_m can be expressed using

$$\Delta\lambda_B = S_\delta \varepsilon_m \lambda_B = (1 - p_e \varepsilon_m) \tag{2}$$

where p_e is the photo-elastic constant of an optical fiber and λ_B is the Bragg wavelength of the FBG. Using the parameters of the single-mode silica fiber, the sensor strain coefficient can be calculated as 1.15 pm/micro-strain. If a temperature shift is applied, two effects are involved. One is the thermal strain induced by the coefficient of thermal expansion of the base material and the other can be attributed to the change of the refractive index of the optical fiber, which is taken into account by the thermo-optic coefficient. Using the parameters of the ordinary single-mode silica fiber, the temperature coefficient can be calculated as 10.6 pm/°C. In the experiment, the raw measured data was processed using the above strain coefficient and temperature coefficient.

2.3. Multiplexing principle

Using the SOA resonant cavity [9], a time division multiplexing (TDM) is proposed. Each of sensors is addressed by using pulse signal with different frequencies in the whole multiplexing system. The resonant cavity configuration of the TDM is shown in Fig. 1. The SOA is driven by a programmable pulse generator drive circuit in a short, high-power pulsed configuration. The two ends of the SOA are connected with the sensor array and a fiber reflector respectively. An optical spectrum analyzer and OSA connecting coupler are used for data analysis. Similar in working principle to the semiconductor laser, the end faces of the SOA's internal gain mediums are coated with antireflection films so that laser could not be generated in the SOA. Two reflectors with a fiber and fiber Bragg grating sensor's end surfaces and the gain media using the SOA constitute an external cavity laser. Fiber reflector is a

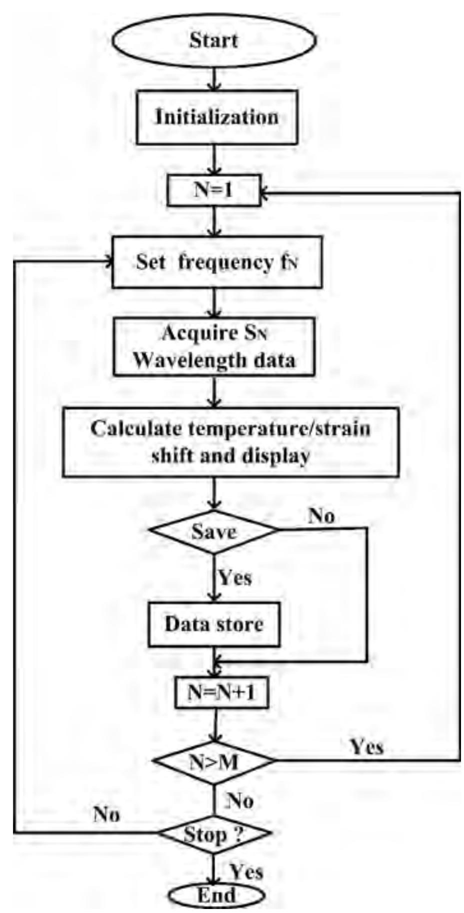

Fig. 2. Flow chart of TDM+WDM program.

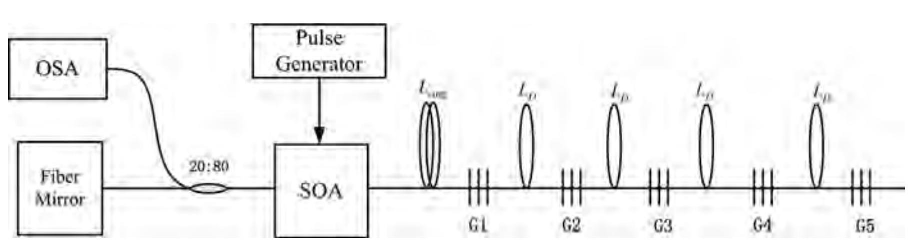

Fig. 1. Resonant cavity configuration of TDM.

broadband reflector and optical fiber grating is a filter which can play a role in wavelength selection. An external cavity laser with this design could operate stable.

When the pulse generator applies a first pulse to the SOA, the both ends of the SOA will generate a short broad-band optical pulse. The left-side light pulse emitted by fiber reflector and right-side light pulse are superimposed into the optical fiber sensor array. When the broadband optical pulse reaches a sensor, the optical pulse signal of the sensor reflecting portion to the semiconductor optical amplifier propagation direction is magnified about 10 dB through the semiconductor optical amplifier. After passing through an optical fiber mirror again and the semiconductor optical amplifier, the weak sensing signal has been magnified two times. The amplified sensing signals and broadband optical signals together pass into the sensing array again. Through repeating the above process, the sensing signal is successively enhanced. Due to the constant total number of photons by SOA generated, the increase of the sensing signal photon numbers reduces the photon number ASE noise and the background noise. The signal-to-noise ratio can be improved greatly. The sensing signal is amplified through multiple reflections between the mirror and grating reciprocation until the SOA reaches the saturated output, which is similar to a semiconductor laser cavity oscillation. The coupler splitting ratio is 20:80, whose 80% power is used for the cavity resonance, and 20% power connected to the power spectrum analyzer is used for measuring the sensor signal. By changing the frequency of the signal generator, different sensors and fiber reflector could constitute the resonant cavity. The sensing signals resonate in the cavity resonance. Thus the sensing signal is amplified and noise is suppressed which improved signal to noise ratio (SNR).

In the TDM+WDM system configuration [10], each of the sensors can be replaced with a group of sensors which have different wavelengths and small sensor space. The SOA light pulse width can simultaneously irradiate all sensors of the group, and the reflected light signal include multiplex sensor's wavelength, whose working principle is similar to that of a single sensor. This group of sensors, fiber reflector and SOA form a resonant cavity. A weak signal will thus be amplified and the SNR is improved. Different frequency pulse signals can access different sensor groups, the measured signal by the wavelength measurement module contain all wavelength data of all sensors to realized reading group multiple sensor data at the same time.

The TDM+WDM mixed technology is defined as each group's sensors are discriminated by using the WDM, and each group access is by using the TDM. If the sensors array is divided into N groups with each group including M low reflectivity sensors, the number of the multiplexing sensors is $M \times N$. The bandwidth of the SOA is more than 40 nm in the experiment, and if each group contains 20 FBG sensors with a bandwidth of 2 nm, more than 1000 sensors could be multiplexed in a single optical fiber using TDM+WDM configuration. In the actual project application, multiplex parameters distributions, such as temperature field, strain field distribution, play a key role in structure health monitoring. By using the TDM+WDM technology [11], a large number of FBG sensors can be multiplexed along one fiber to realize multiplexed measurement points.

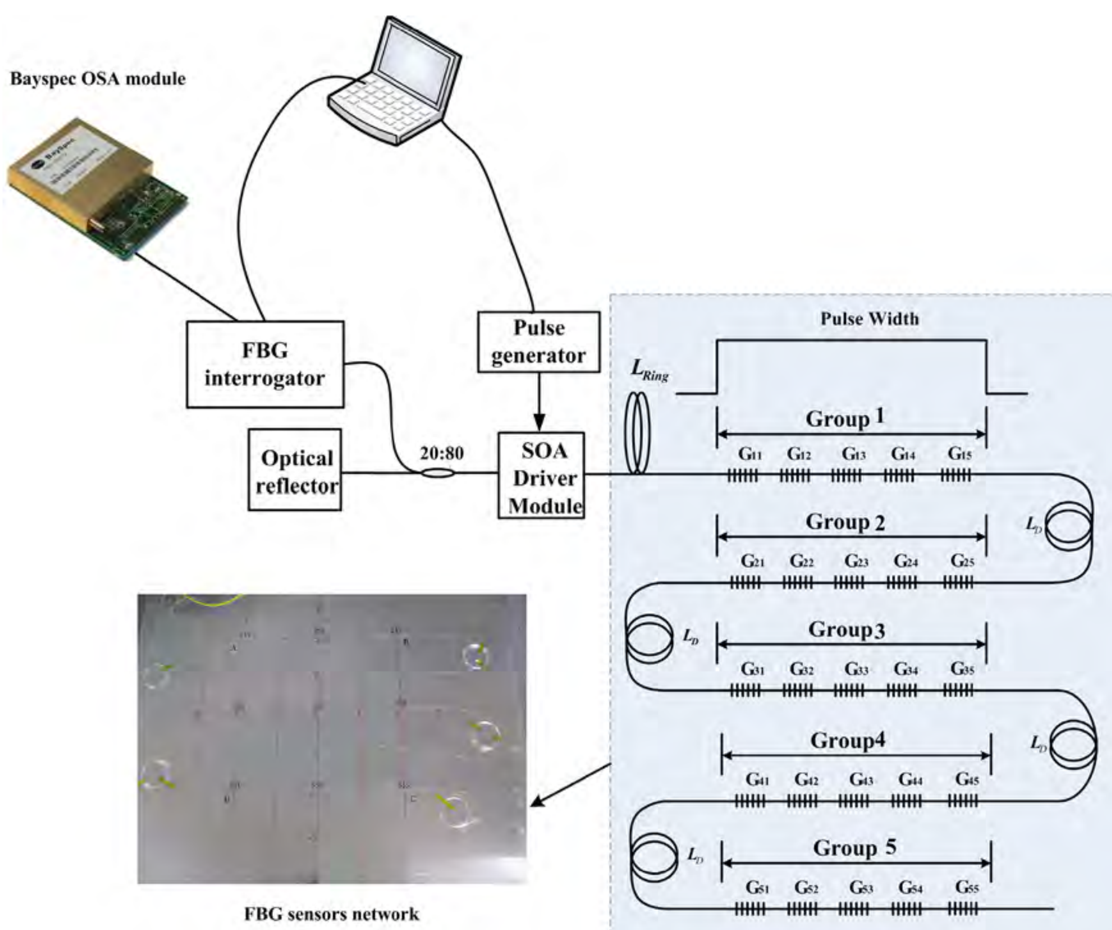

Fig. 3. FBG sensors system based on TDM+WDM.

2.4. Data processing method

In the experiment, the resonant cavity configuration of the optical fiber grating sensing scheme is addressed by setting the frequency of the signal generator to acquire the sensors' data through an OSA, which is not suitable for real time monitoring in practical application. In order to achieve signal demodulation of the sensor, TDM+WDM configuration based software is designed for distributed strain/temperature measurement. In fiber grating sensors the measurement information is wavelength encoded and directly measured through a wavelength shift data. TDM system use time addressable features that means the light's transit time between the sensor and the light switch is utilized. To enable sensing array scanning, the relevant frequency to the sensors nods to be set through software. The computer transmits the relevant frequency to a pulse signal generator, and achieves different frequency scanning.

Based on LabView virtual instrument, The TDM software system has the capacity of the data input, display and storage. The flow diagram as shown in Fig. 2 indicated the system working process in details. Firstly, system initialization; secondly, according to the optical pulse flight time from the light source to the N sensor, a loop routine is designed for scanning all sensors by setting frequencies. The system could collect the wavelength data of the sensor when corresponding frequency reaches the sensor. Each sensor could be addressed by setting corresponding frequency. Meanwhile sample the wavelength of the addressed sensor and process the data. Thirdly, judge if to save data and increase the index of sensor N, if the index is larger than the numbers of sensors, then setting the index to one. At last, repeat the above work, all sensors can be addressed and display the strain or temperature in real time. The entire sensor array can be scanned and the wavelength shift is displayed as the temperature, strain and other parameters by incorporating the sensitivity values.

3. Results and discussion

3.1. Monitoring the stress field distribution

In order to test the sensing system model developed in the previous section, based on TDM+WDM technology, a FBG sensors system with 25 low reflectance FBG sensors is configured as shown in Fig. 3. The sensors are divided into five groups, with each group consisting of five FBG sensors with central wavelengths of 1546, 1548, 1550, 1552 and 1554 nm. The sensors were attached to the surface of $80 \times 80 \times 0.18\ cm^3$ aluminum plate. The spatial distance between two FBG stations is 10 cm over a length of 6 m.

The resonant cavity configuration of the TDM+WDM, coupled with the LabView based data acquisition is used to display the whole-field strain distribution of the aluminum plate. Five frequencies (637 kHz, 602 kHz, 571 kHz, 543 kHz and 517 kHz) were

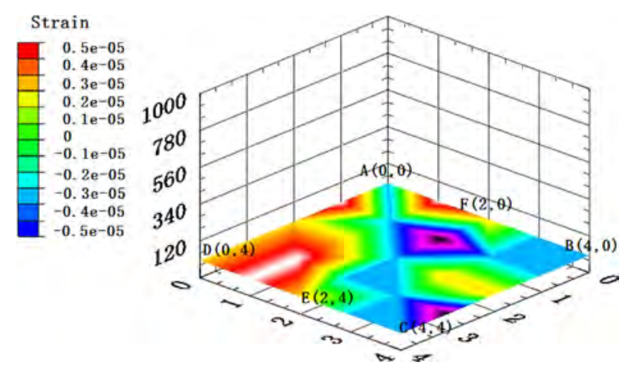

Fig. 5. Strain distribution in aluminum plate with no load.

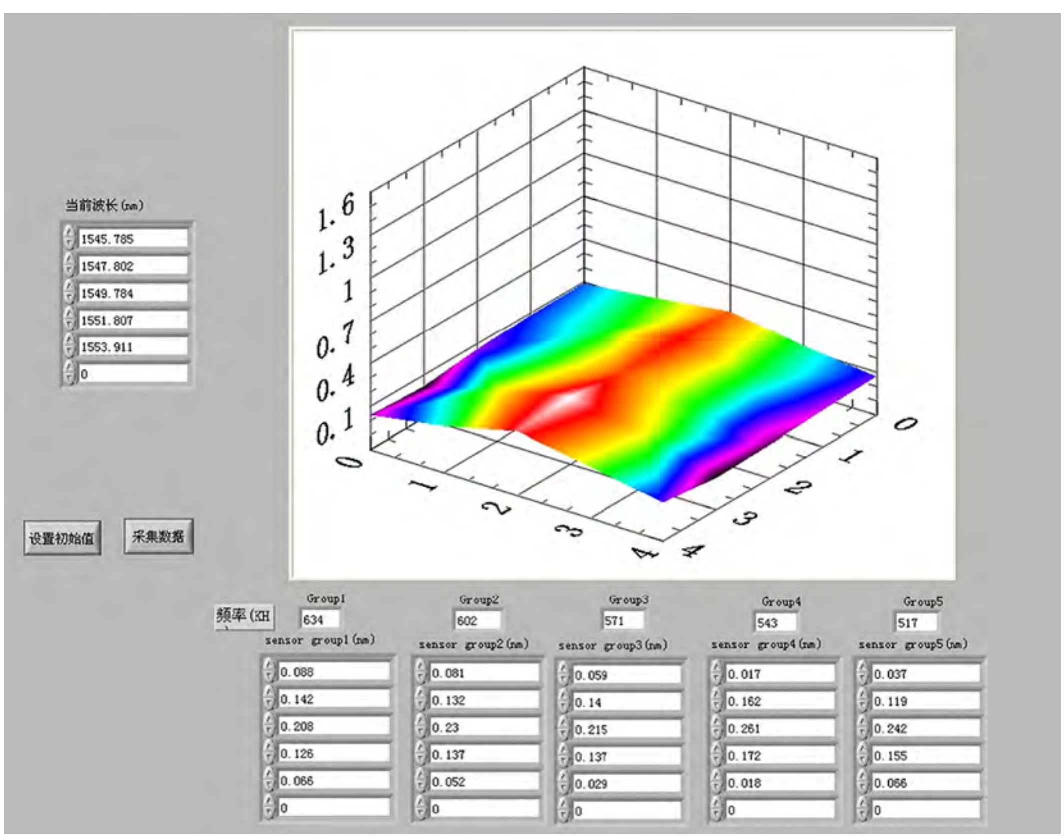

Fig. 4. Interface of software.

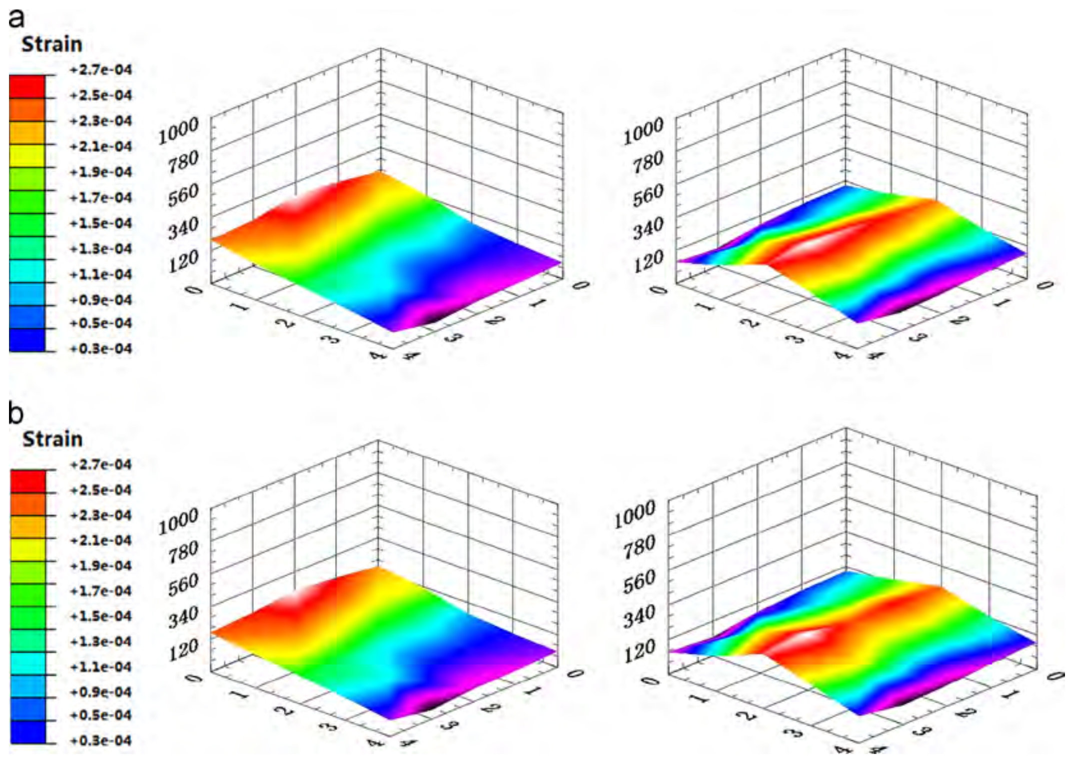

Fig. 6. Schematic of strain distribution using (a) gauge and (b) FBG sensors measurements under different loads.

sent to the each senor and five wavelengths were acquired and set as the initial reference wavelength. When the system starts collecting the data, PC software will send the relevant frequency of each sensor and compare the measured wavelength with the initial wavelength to get the wavelength shift.

When the five groups of sensor arrays' are sequentially acquired and processed the wavelength shift, which can be converted to strain or temperature. The software interface is shown in Fig. 4.

In the strain distribution pattern, coordinate (0, 0), (4, 0), (4, 4), (0, 4), (2,4), (2,0) respectively correspond to aluminum A, B, C, D, E, F six points as shown in Fig. 5. When the aluminum is not affected by external force, the strain distribution could be seen from Fig. 5. The data storage for each scanning obtained at various points are not identical due to the last measurement's affections and wavelength measurement module's measurement error (around 5 pm), thus there are different color depths in various regions at initial station. However, the strain distribution pattern paralleled with the horizontal plane, the different color depths would not affect next measurement process.

25 external strain gauges were attached near to the FBG sensors respectively for reference measurement to prove the performance of the TDM+WDM system for strain distribution measurement. The comparison results between the measure data of the external strain gauges and the FBG sensors are shown in Fig. 6 for two conditions: an applied load of 10 N at points A and D; at points E and F. From Fig. 6, it can be clearly seen that strain distributions are almost the same. There is some difference due to the difference in strain transfer mechanism of the strain gauge and the FBG sensor. The strain gauge is a thin foil; while the grating is on a cylindrical fiber, with aluminum connections through the adhesive to achieve, from the area of contact is greater strain sheet, aluminum by adhesive agent delivered to the strain gauge strain lower losses. For the same number of measurement points, FBG system sensor configuration is much simpler; with one fiber can provide multipoint measurement, while each strain gauges need two wires resulting multiple wire connections.

3.2. *Monitoring the temperature field distribution*

The five points where the strain distribution was measured could be used for temperature measurement as well. Due to limited number of thermoelectric coolers, the aluminum plate is divided into five main points G, H, I, J, and O corresponding to the coordinates (1,3), (1,1), (3,1), (3,3), and (2,2).

Fig. 7(a) shows the temperature distribution when heat is applied to the center of the plate. The maximum temperature is at point O as expected. Next heat was applied at points G and I, and the resulting temperature distribution is shown in Fig. 7(b). Finally points G and H, G and J were heated separately, when the temperature stabilized, the temperature distribution map shown in Fig. 7(c) and (d) were observed. The results show the capability of the FBG strain sensor to monitor temperature fields as well.

4. Conclusion

Based on the combination of wavelength and time division multiplexing technique, a novel fiber Bragg grating (FBG) sensor multiplexing system has been designed and investigated. The multiplexing sensor number of the scheme could be theoretically increased up to 1000 using the WDM and TDM technique. The strain/temperature distribution monitoring experiment were accomplished with 25 FBG sensors multiplexing. Considering the advantages of large multiplexing capacity, low insertion loss, simple manufacture process and low cost, and the proposed sensing scheme shows great potential in the distributed sensing applications of the large structure.

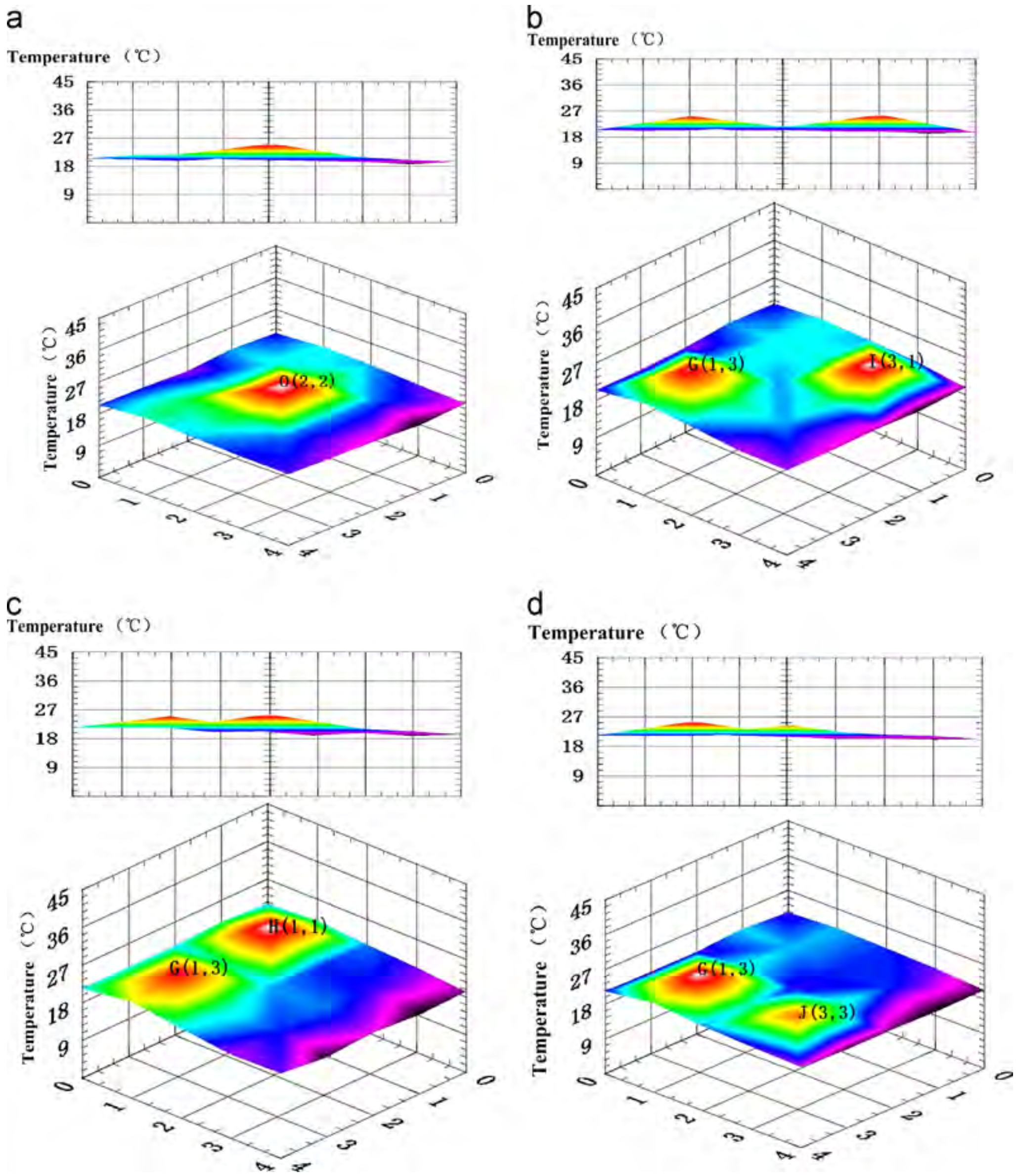

Fig. 7. Schematic of temperature distribution under different points.

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