Optics and Lasers in Engineering 59 (2014) 19–24

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

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

Yongbo Dai [a], Peng Li [a], Yanju Liu [b], Anand Asundi [c], Jinsong Leng [a,*]

[a] Centre for Composite Materials and Structures, Harbin Institute of Technology (HIT), No. 2 YiKuang Street, Harbin 150080, PR China
[b] Department of Aerospace Science and Mechanics, No. 92 West DaZhi Street, Harbin Institute of Technology (HIT), Harbin 150001, PR China
[c] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

ARTICLE INFO

Article history:
Received 7 November 2013
Received in revised form
23 February 2014
Accepted 26 February 2014
Available online 20 March 2014

Keywords:
Fiber Bragg grating sensors
Wavelength division multiplexing
Time division multiplexing
Strain/temperature field distribution

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].

* Corresponding author. Tel./fax: +86 451 86402328.
E-mail address: lengjs@hit.edu.cn (J. Leng).

http://dx.doi.org/10.1016/j.optlaseng.2014.02.011

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

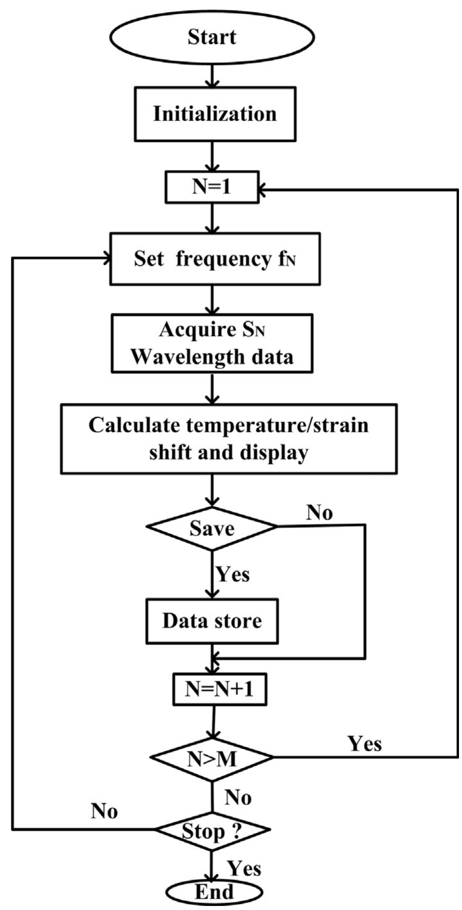

Fig. 2. Flow chart of TDM+WDM program.

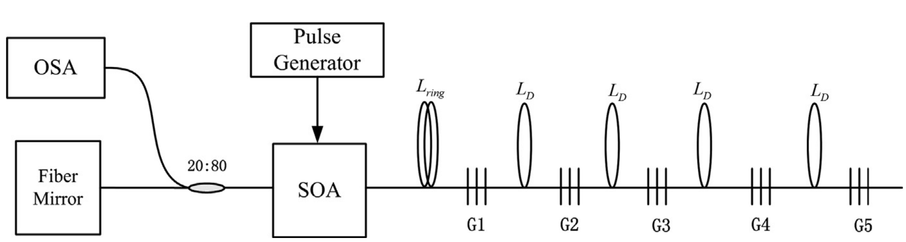

Fig. 1. Resonant cavity configuration of TDM.