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Design of a Strain Sensor Based on Cascaded Fiber Bragg Grating for Remote Sensing Monitoring

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Abstract**—**Harsh environments require developed detection by an optical communication system to ensure a high level of security and safety. Fiber Bragg gratings (FBGs) are emerging sensing instruments that respond to variations in strain and temperature by varying wavelengths. In this study, a cascaded uniform FBG is designed as a strain sensor for 6 km length at 1550 nm wavelength with 30 °C temperature by analyzing dynamic strain and wavelength shifts. The FBG is placed in a small segment of an optical fiber that reflects light with a specific wavelength and passes on the remaining wavelengths. Consequently, periodic alteration occurs in the refractive index in the fiber core. The alteration in the modal index of the fiber is produced by strain effects on a Bragg wavelength. When the developed sensor is exposed to the strain (0.01) of the cascaded uniform FBG, the wavelength shifts by 0.0000144383 μm. The sensing accuracy of the developed sensor is 0.0012. Simulation results show the reliability and effectiveness of the strain monitoring sensor for remote sensing application.

Keywords**—**Remote sensing, cascaded fiber Bragg grating, strain sensor, wavelength shift.

I. Introduction

MONITORING of environmental issues is crucial for increasing security and effectual allocation of resources, such as petroleum, natural gas, and cultivated land. Unpredictable variations that cause ecological or human health hazards must be monitored in temporal and spatial domains. However, monitoring technologies focus on the investigation of chemical and physical features of environments [1], [2].

One of the most essential components of model tests on combustible internal explosions is strain measurement. Strain gauges are used to measure strain in traditional electrical measurement methods. Traditional electrical methods have various limitations, such as susceptibility to electromagnetic interference, short life, and inability to distribute. Meanwhile, optical fiber sensors (OFSs) show potential for use in harsh environments. OFSs have low heat loss and large data bandwidth compared with electronic sensors [3], [4]. In 1978, Ken Hill discovered FBG at the Communication Research Centre in Canada [4]. FBG has elicited much attention in optical sensing applications due to its merits, such as low cost, long service life, small size, real-time response, simple networking, high accuracy, high sensitivity, good reusability, and immunity to electromagnetic interference. In addition, FBG demonstrates high performance in sensing different parameters, such as strain, temperature, pressure, humidity, stress, and refractive index (RI), by using grating-based devices. FBG is adopted in many current applications, including high-temperature sensors, health and biomedical devices, structural engineering, industries, radioactive environment, aerospace, and civil engineering [2], [3], [5].

FBG sensors were developed as safety monitoring sensors in several extant studies via analysis or sensing principles. Gao et al. [6] used FBG to develop useful sensing tools that respond to changes in stress, strain, and temperature by changing wavelengths. Ou et al. [7] and Chan et al. [8] applied FBG sensors in the structural health monitoring of bridges, including 40 grating sensors for strain monitoring at different portions, and achieved good monitoring results.

The current study tests the strain monitoring performance of a cascaded FBG sensor for remote sensing monitoring application at 1550 nm wavelength. A detailed simulation study of FBG and its deployment in different applications is conducted. The sensing of physical parameters, such as strain, and RI is also discussed.

II. Theory and Principle

The sensing principle of the uniform FBG sensor is based on wavelength shift. Based on coupled mode theory, Bragg wavelength depends on the physical parameters of the fiber, which are grating period and effective RI. Wavelength shifting of the reflected spectrum is due to the period of grating or effective RI of FBG, and it is changed by the parameters to be measured, such as temperature, strain, humidity, and pressure. The shifting is either to the left or right of the central wavelength. Hence, a change in n_{eff} results in a change in Bragg wavelength, which is calculated as [1], [2], [5], [6]:

$$\Delta\lambda = 2n_{eff}\,\Lambda, \qquad (1)$$

where $\Delta\lambda$ is the free space wavelength of the input light reflected from the grating, n_{eff} is the effective RI of the fiber core at the free space center wavelength, and Λ is the grating period of the uniform FBG. In addition, uniform grating can be expressed as the sinusoidal modulation of fiber core RI as [5]:

$$n(z)= n_{core} +\delta_n\,[1 + \cos(2\pi z/\Lambda +\varphi(z))], \qquad (2)$$

where n_{core} is the core RI when it is not radiated and δ_n is the amplitude of induced RI differences.

Uniform FBG implements the basic technique of reflection, dispersion, and filtering and can be easily applied in sensing applications. The uniform FBG wavelength changes with strain

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and temperature as [4]:

$$\frac{\Delta\lambda}{\lambda_{\circ}} = k\ \varepsilon + \alpha_{\delta}\ \Delta T, \quad (3)$$

where $\Delta\lambda$ is the wavelength shift, $\lambda_{\circ}$ is the base wavelength at launch, k is the gage factor [k = 1-p, in which p is the photo-elastic coefficient (p = 0.22) and k = 0.78], ε is the strain, ΔT is the temperature change in Kelvin, and α_{δ} is the change in RI (α_{δ} = 5….8 x 10^{-6}/K) [4].

The sensitivity of Bragg wavelength strain is expressed as [6]:

$$\Delta\lambda_{B} = [\lambda \frac{\delta n}{\delta t} + n \frac{\delta \Delta}{\delta x}]\ \Delta l, \quad (4)$$

where Δl is the differences in FBG length affected by strain.

III. Simulation Details

The design of a strain sensor based on cascaded FBG for remote sensing monitoring application is constructed. The developed design is simulated using Optisystem software. The developed model comprises a white light source, optical null, optical delay, bidirectional optical fiber, and cascaded uniform FBG. The white light source generates the input signal, which has a frequency of 193.1 THz and input power of –130 dBm. Moreover, the white light source has a wide optical bandwidth and radiates visible white light. Consequently, the input signal is passed through bidirectional optical fibers of 6 km length with 30 °C. Optical null is applied to terminate the bidirectional optical fiber connection and increase the measurement accuracy. Optical delay is utilized to provide accuracy for optical path variation. Optical delay controls the delay through the device by changing the distance at which light propagates between the input and output power. Bidirectional optical fibers are utilized with cascaded uniform FBG as sensors. The cascaded uniform FBG has a bandwidth of 125 GHz and frequency of 193.1 THz. The selected reference wavelength of 1550 nm provides low attenuation and absorption losses.

A collection of the scattered signals is detected in a bidirectional optical fiber. The global simulation parameters selected for bidirectional optical fibers are shown in Table I. Furthermore, an optical spectrum analyzer is used to measure and display the distribution of optical source, transmitted, and reflected power. An optical power meter is applied to measure the transmitted and reflected power.

TABLE I
Simulation Parameter Settings for the Bidirectional Optical Fibers

Parameters	Values
Reference wavelength (nm)	1550
Attenuation (dB/km)	0.2
Effective area (μm^2)	80
Polarization factor	2
Temperature (K)	303
Length (km)	6

IV. Results and Discussion

A strain sensor based on cascaded uniform FBG is constructed with a bidirectional optical fiber with 6 km length and 30 °C temperature. The simulation and investigation of the developed design are performed using the Optisystem simulator 7.0 software. A schematic of the cascaded uniform FBG sensor setup used for remote sensing monitoring is shown in Fig. 1. The novelty of the developed simulation design is the cascaded uniform FBG sensor application, which results in excellent performance of transmitted and reflected power demonstration. At the bidirectional optical fiber port terminals, the optical power meters and optical spectrum analyzers are connected at the input and output ports to measure the transmitted and reflected power.

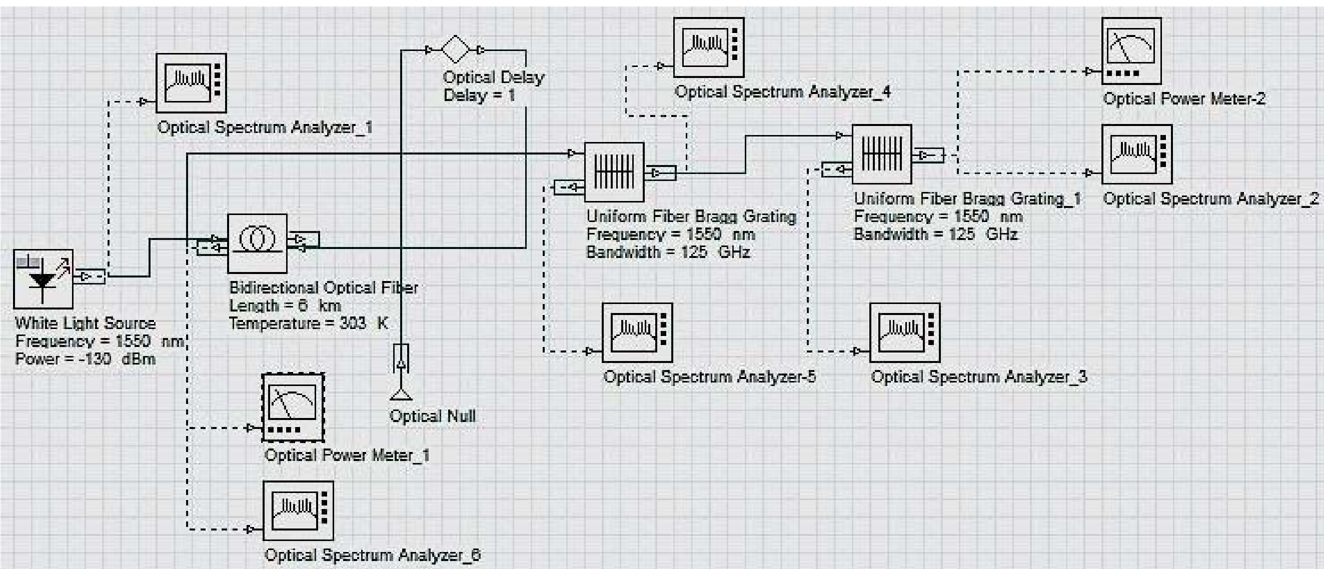

Fig. 1 Cascaded uniform FBG for remote sensing in the simulation using the Optisystem software

Different simulation values of strain are adopted to analyze the performance of the cascaded uniform FBG sensor and corresponding wavelength shifts by using Optisystem software. The developed system is implemented at 1550 nm, and the input power is −130 dBm. Fig. 2 shows the power spectrum of the input signal.

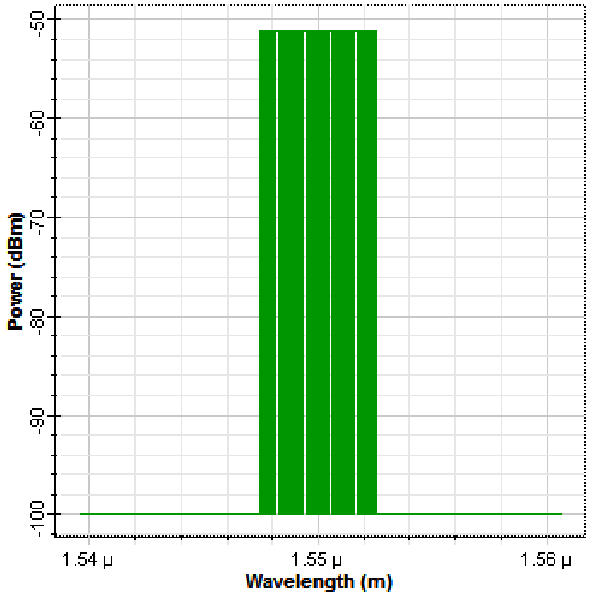

Fig. 2 Power spectrum of the input signal

The transmitted and reflected signal power spectra are presented in Figs. 3 and 4, respectively.

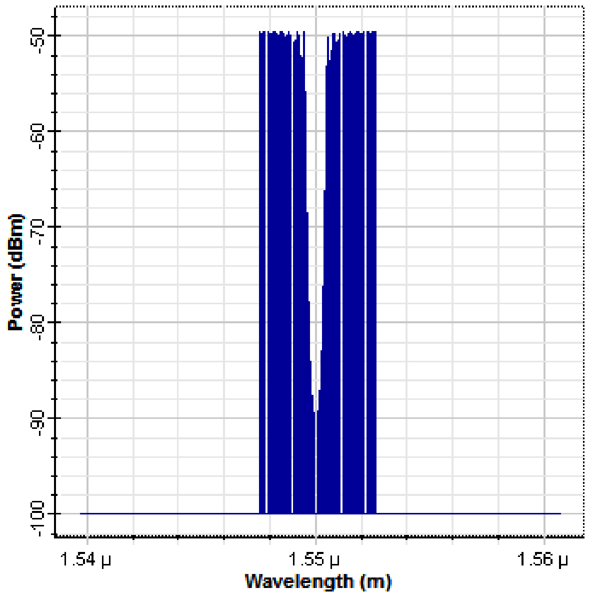

Fig. 3 Power spectrum of the transmitted signal

The wavelength shifting of the proposed model resulted in a reference wavelength of 1550 nm and 30 °C temperature, as shown in Table II. This model that uses a bidirectional optical fiber of 6 km with two uniform FBGs is compared with the model in [6]. In general, the simulation design is characterized by excellent signal performance of transmitted and reflected power spectra. The developed design produces a high-quality, high-accuracy signal of transmitted and reflected power spectra compared with the design of [6].

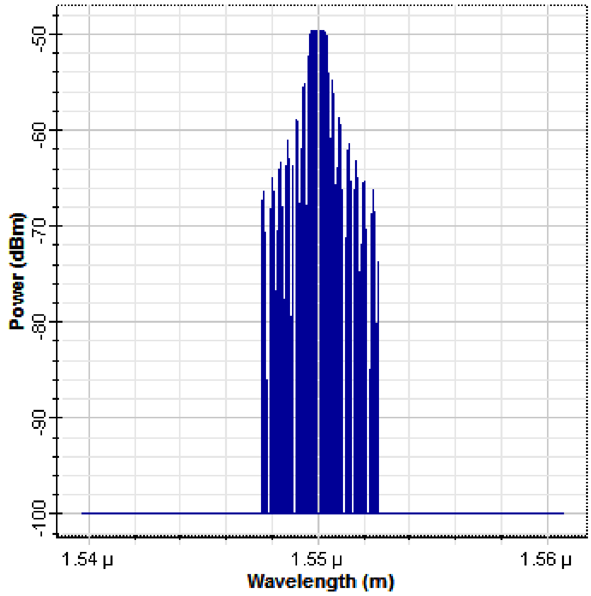

Fig. 4 Power spectrum of the reflected signal

TABLE II
WAVELENGTH SHIFTING

Initial Wavelength λ_B (nm)	Temperature (°C)	Strain by cascaded uniform FBG	Wavelength Shifted $\Delta\lambda$ (µm)
1550	30	0.005	0.0000083933
1550	30	0.006	0.0000096023
1550	30	0.007	0.0000108113
1550	30	0.008	0.0000120203
1550	30	0.009	0.0000132293
1550	30	0.01	0.0000144383

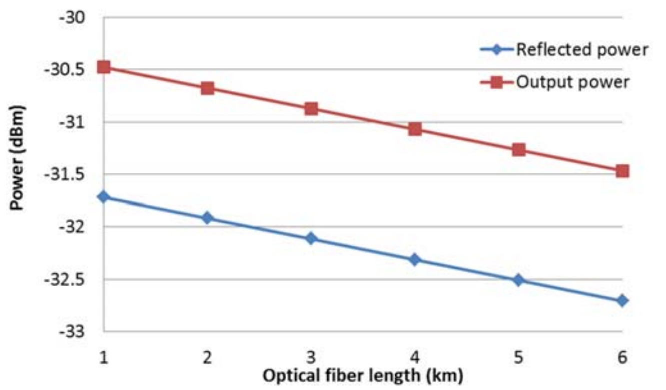

Fig. 5 Optical fiber length versus output and reflected power

Fig. 5 shows the relationship between optical fiber length and output and reflected power. The power values are recorded from 1–6 km of optical fiber length. The values of transmitted and reflected power decrease with the increase in optical fiber length. Fig. 6 depicts a linear relationship between strain and wavelength shift obtained from the developed cascaded uniform FBG sensor. From the slope of the fitted line shown in Fig. 6, the wavelength shift is obtained, and the sensing accuracy is 0.0012. Overall, the developed strain sensor has clear sensitivity advantages over other related sensors reported in extant literature. As shown in Figs. 5 and 6, the proposed model has several advantages in terms of high linearity, signal transmitted power, reflected power, and signal quality performance with low losses compared with [6].

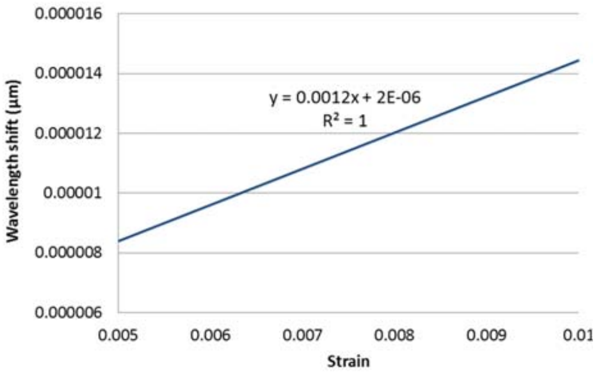

Fig. 6 Linear relationship between strain and wavelength shift

V. Conclusion

A strain sensor using cascaded uniform FBG is proposed and demonstrated via the Optisystem simulator. The reference wavelength of the developed sensor is 1550 nm, and the applied temperature is 30 °C. The uniform FBG sensor's wavelength changes with the change in RI. The strain sensor is characterized by excellent dynamic performance, and a linear relationship with wavelength shift is observed at 6 km optical fiber length. At 6 km optical fiber length, the output power is −32.707 and the reflected power is −31.466. The results indicate that the sensor has high performance and accuracy and could be used in data communication systems and remote sensing applications.

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