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Response characteristics of fiber Bragg gratings irradiated by high energy lasers

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Abstract: The response characteristics of a Fiber Bragg Grating(FBG) irradiated by high energy laser beams are investigated both theoretically and experimentally to explore the possible applications of the FBG to High Energy Laser(HEL) parameter measurements. The thermal response characteristics of the FBG irradiated by HEL beams are obtained by solving the heat transfer equation using certain approximations. The resonance wavelength information of the FBG is recorded with an interrogator. The experimental results show that the maximum resonance wavelength shift of the FBG changes linearly with the irradiating power density within a certain range, which agrees with the results of numerical simulation.

Key words: fiber Bragg grating; laser radiation; high energy laser; response characteristics

高能激光辐照下光纤布拉格光栅响应特性

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摘要:为探索光纤布拉格光栅在高能激光参数测量方面的应用,通过实验和数值模拟研究分析了其在高能激光辐照下的响应特性。通过解传热方程,获得了光纤布拉格光栅在高能激光辐照下的热响应特性。利用一个光纤光栅解调仪,记录了光纤布拉格光栅在高能激光辐照下的波长漂移现象。实验结果表明:在一定的功率密度范围内,光纤布拉格光栅的最大波长漂移与其所受的辐照功率密度成线性关系,该结果与理论模拟相符。

关 键 词:光纤布拉格光栅;激光辐照;高能激光;响应特性

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1 Introduction

High Energy Lasers (HELs) are crucial in industrial and scientific applications. With rapid development and upgrading of HELs such as carbon dioxide lasers, Solid State Diode-pumped Lasers (SSDPL), Chemical Oxygen-iodine Lasers (COIL) and Hydrogen-fluoride/Deuterium-fluoride lasers (HF/DF)[1-2], the parameter measurements of those lasers are becoming an outstanding problem[3]. Current measurement methods mainly include burn-in method, calorimetric method[4] and electro-optical sensor method[5]. However, in these methods, most of them require complicated engineering design, and laser beams need to be blocked, split, reflected or scattered. It raises problems for HELs resistance, which is a much tougher task for the future intense laser systems[6].

Since the appearance of Fiber Bragg Gratings (FBGs), people have been thinking about their applications in sensing. After decades of fast development, FBG sensors are covering a wide range of fields[7], such as geological science, civil engineering, aviation, medicine and chemistry.

In this paper, we investigate the response characteristics of FBGs under HEL beam radiation to explore the potential application of the FBG in HEL measurement.

2 Experiments and Simulation

Laser radiation of the fiber leads to temperature changes, resulting in the index gradient (photo-thermal effect) and strains (thermal expansion and photo-elastic effect)[8-9]. As the shift of the FBG caused by strain effect is much smaller than that directly caused by temperature change[10], only the temperature change is considered in our model. Given the small diameter of the fiber, the radial heat transfer in the fiber is negligible compared with that along the fiber[10-11].

First, the temperature features of the FBG should be revealed. An ESPEC MT3065 incubator is used to provide the stable temperature environment, and an I-MON 512E-USB interrogation monitor is used to record the resonance wavelength shift of the FBG, the relationship between the resonance wavelength shift and the temperature change of the FBG is obtained as:

$$\Delta\lambda = 9.76 \times 10^{-3} \times \Delta T , \tag{1}$$

Here the parameters used are all in SI unit. This result coincides with the statement in Ref. [10].

For position x with a length of Δx along the fiber, when irradiated by a laser beam, the heat transfer equation should be:

$$\frac{\Delta T(x,t)}{\Delta t} = \frac{1}{\rho c}\left\{\frac{\alpha I(x,t)}{r} - \frac{2h[T(x,t) - T_0]}{r} - \frac{2\varepsilon\delta[T^4(x,t) - T_0^4]}{r} + k\frac{T(x-\Delta x,t) - 2T(x,t) + T(x+\Delta x,t)}{(\Delta x)^2}\right\} , \tag{2}$$

where the term 1 – term 4 stand for the absorption, the heat convection with the surrounding air, thermal radiation; and the heat conduction, respectively. Descriptions of the symbols used in this paper are listed in Table 1.

Tab. 1 Parameters used in this paper

Symbol	Description	Value
α	Sorption coefficient	Derived from the experiment
$I(\bar{I})$	Power density(average)	Adjustable W/m^2
r	Radius of the fiber	62.5 mm
R	Radius of the laser beam	8 mm
h	Convection coefficient	Derived from the experiment W/(m^2 · K)
T_0	Room temperature	295 K
k	Heat conductivity	1.7 W/(m · K)[11]
ε	Emissivity of the fiber	0.94
δ	Stefan-Boltzmann constant	5.67×10^{-8} W/(m^2 · K^4)
ρ	Density of the fiber	2 200 kg/m^3 [10]
c	Heat capacity of the fiber	730 J/(kg · K)[10]
h'	Effective heat loss coefficient	Derived from the experiment W/(m^2 · K)

The radiation experiment setup is shown in Fig. 1. The high power fiber laser is used to simulate the HEL radiation situation with a center wavelength at 1 070 nm. The FBG is written in a SMF-28 fiber with a grating region of 10 mm. In the experiment, the coating layer is removed to protect the grating region from being burned. The FBG was irradiated with different laser power densities ranging from 100 to 600 W/cm^2 with a laser duration of 5 s. And the laser beam is 16 mm in diameter which can cover the whole grating region of the FBG.

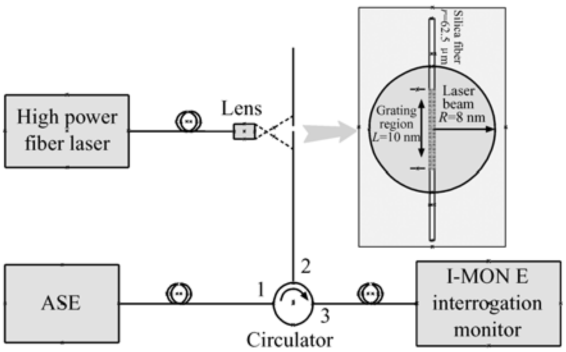

Fig. 1 Schematic diagram of the FBG response experiment. The inset shows the dimension of the irradiation situation. The ASE is a broadband light source covering from 1 510 to 1 580 nm.

Solid lines in Fig. 2 record the experimental rise curves of the resonance wavelength of the FBG irradiated with different laser power densities.

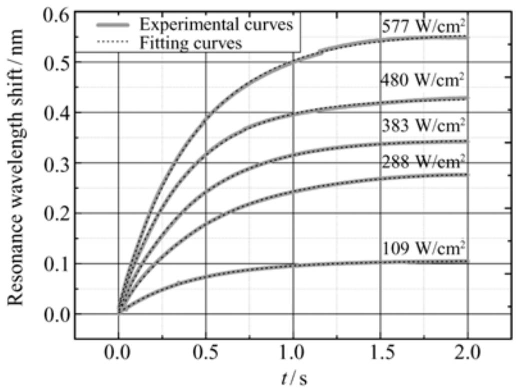

Fig. 2 Experimental rise curves of the FBG irradiated with different laser power densities and their fitted lines.

Fitting of those curves in Fig. 2(shown in black dashed) with single exponential growth functions gives a same time constant $\tau=0.436$ s, independent of the laser power density. It is suggested that the heat loss is linearly proportional to the temperature change of the FBG[10]. Thus, the thermal radiation term in Eq. (2) can be approximated as proportional to the temperature change[12].

For the sake of simplicity, take the irradiated region, including the 10 mm grating region, as a whole, thus, $\Delta x=2R$. Correspondingly, take $\bar{I}$ as the average power density irradiated on the fiber. As indicated in Ref. [11], due to the small conductivity of the fiber, the sideward fiber is hardly heated, which means the temperature of the sideward fiber can be taken as the room temperature. An effective heat loss coefficient h' is introduced and it contains the convection term and the thermal radiation term, and setting $\Delta t \to 0$, we get:

$$\rho c \frac{\mathrm{d}T(t)}{\mathrm{d}t} = \frac{\alpha \bar{I}(t)}{r} - \left(\frac{k}{2R^2} + \frac{2h'}{r}\right)[T(t) - T_0] . \quad (3)$$

It has the same form with the one in Ref. [9]. At steady-state, we get:

$$\frac{\alpha \bar{I}(t)}{r} - \left(\frac{k}{2R^2} + \frac{2h'}{r}\right)(T_{\max} - T_0) = 0 . \quad (4)$$

Solving Eq. (3), the explicit expression of $T(t)$ is:

$$T(t) = -\left(T_0 + \frac{\alpha \bar{I}}{r\left(\frac{2h'}{r} + \frac{k}{2R^2}\right)}\right)\exp\left(-\frac{t}{\tau}\right) + T_0 + \frac{\alpha \bar{I}}{r\left(\frac{2h'}{r} + \frac{k}{2R^2}\right)} , \quad (5)$$

where $\tau = \frac{\rho c}{\frac{2h'}{r} + \frac{k}{2R^2}}$ is the time constant. Together with Eq. (4), the absorption coefficient is derived as:

$$\alpha = \frac{r\rho c(T_{\max} - T_0)}{\tau \bar{I}} . \quad (6)$$

Since $\tau = 0.436$ s, we get the value of the effective heat loss coefficient $h' = 1.15 \times 10^2$ W/(m^2·K), which is very close to the one derived in Ref. [10].

The maximal resonance wavelength shift of the FBG under different laser power densities is presented in Fig. 3 with filled squares. Linear fit indicates that the maximal resonance wavelength shift changes linearly with the laser power density with the coefficient of determination being 0.997 when the laser power density is smaller than 600 W/cm^2.

Exploiting the maximal wavelength shift at 109 W/cm^2 in Fig. 3, together with Eq. (6), we obtain the absorption coefficient $\alpha = 2.28 \times 10^{-3}$. It should be noticed that this value is measured in outdoor environment where the dust on the surface of the fiber may contribute a large part to the effective absorption coefficient. This explains the difference between this effective absorption coefficient and the one of fused silica[13]. Together with those listed in Table 1, these parameters can be used to calculate the time responses of the FBG irradiated by any amount of power density and duration.

Simulation results of the maximal resonance wavelength shift and the time response of the FBG are shown in Fig. 3 and Fig. 4, respectively. The experimental and simulation results agree well with each other.

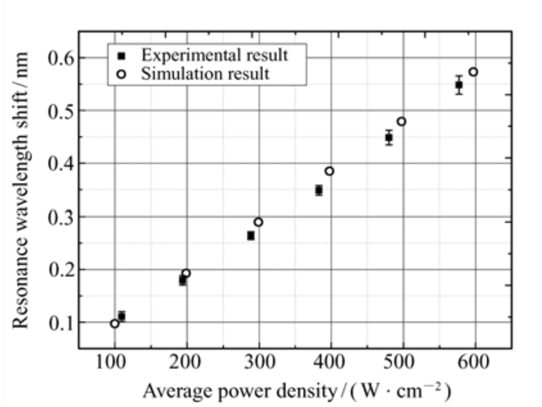

Fig. 3 Maximal resonance wavelength shift under different laser power densities.

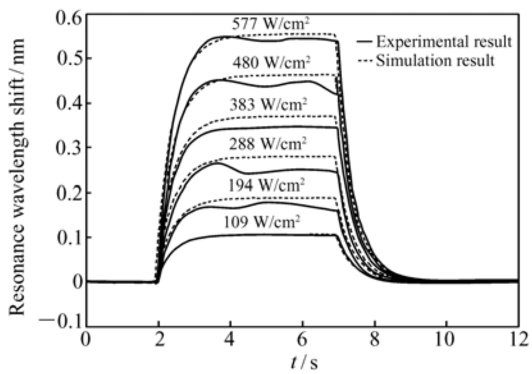

Fig. 4 Experimental and numerical time response of the FBG at different laser power densities with a duration of 5 s.

3 Discussions

When irradiated by HEL beams, the fiber absorbs part of the energy and gets heated. However, owing to a small absorption coefficient in the near infrared range(0.8 – 2 μm), and a large surface area to volume ratio, the fiber can reach equilibrium in just a few seconds, resulting in limited temperature rise. And the maximal resonance wavelength shift of the FBG changes linearly with irradiating power density in a certain range. During the experiment, one bare FBG was irradiated with a power density of 6 000 W/cm^2 for one minute, and no damage was found in the reflective spectrum, which indicats that FBGs can withstand long period radiation of HELs and it is more suitable for long time measurement of HELs.

However, further improvement is required for this system. As we can see in Fig. 4, differences exist between experimental curves and numerical ones. The possible reason would be the instability of the beam profile during the irradiating process. In addition, in our model, we assume the absorption coefficient α and the effective heat loss coefficient h' as constants which means they don't change with the temperature. But, in fact, they are temperature-dependent values[11]. This will also lead to the difference between the experiment and the simulation.

The major concern is the non-uniform temperature distribution of the grating region caused by the Gaussian distribution of the laser beam. This leads to the chirp and broadening of the reflective spectrum[10]. Fig. 5 shows the spectrum evolution during laser radiation process at high power density. With multi-peaks, the interrogation monitor which generates the resonance wavelength of the FBG with a Gaussian fit of the spectrum, can't present the actual wavelength shift of the FBG.

To improve the system, the laser power distribution along the grating region should be smoothed,

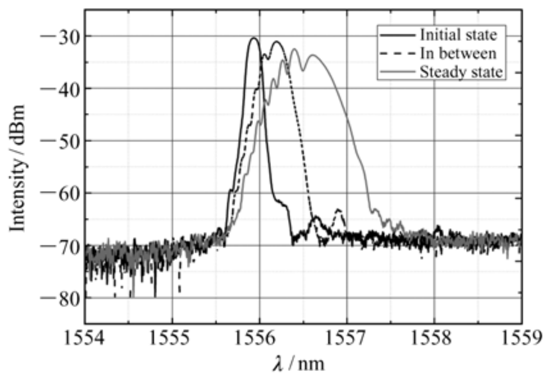

Fig. 5 Reflective spectra of the FBG under laser irradiation measured with an Agilent 86140B Spectrum Analyzer
The black solid line is the reflective spectrum of the FBG at normal state. The black dashed shows the change of the spectrum during the rise time(as shown in Fig. 2). And the grey solid line is the steady state spectrum when the heat transfer of the grating region reaches equilibrium.

where FBG s with much shorter grating regions would be a good choice. Furthermore, the interrogation method should be perfected. Package of the FBG sensor is also determinative, which will seriously affect the stability, sensitivity and dynamic range of the FBG sensor. Future work in this field will focus on these aspects.

4 Conclusions

Response characteristics of FBGs irradiated by HEL beams are studied, which offers a potential method to HEL parameter measurements in the near infrared range. This system can withstand extremely strong laser radiation to offer a long-time record for the laser parameters and avoid a complicated engineering design. Given the small volume of FBG, multipoint FBG sensors or FBG arrays may provide detailed distribution information for large beam profiles of HELs.

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