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Linearly Chirped Fiber Bragg Grating Based Temperature, Strain and Pressure Sensors

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Abstract

Fiber Bragg grating (FBG) sensors are one of the most exciting developments in the field of optical fiber sensors in recent years. Compared with conventional fiber-optic sensors, FBG sensors have an umber of distinguishing advantages. In this paper the basic characteristics and the fundamental properties of strain, temperature and pressure sensor based on linearly chirped FBG (LCFBG) are described. The change of applied strain with the temperature has also been studied to obtain zero shifts of Bragg wavelength for enhancing the performance of FBGs.

Keywords: Optical fiber sensor, temperature, strain, pressure, Fiber Bragg Grating, Bragg wavelength.

1. INTRODUCTION

A fiber Bragg grating is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others [1]. This is achieved by adding a periodic variation to the refractive index of the fiber core, which generates a wavelength specific dielectric mirror. In recent years, many research and development projects focused on the study of fiber Bragg gratings [2-3]. FBG are provided to be one of the most important components in optical communication links in different applications as all-optical routers, very selective filters, gain equalizers, sensors and dispersion compensators [3]. A sensor is a transducer that responds to the quantity being measured. Optical fiber sensor technology based on Bragg gratings has use in a number of important areas including basic quasi-distributed sensors based on Bragg gratings, chirped grating sensing, fiber Bragg grating laser sensors, long-period grating sensors and interferometer configurations based on gratings [4]. The techniques discussed will primarily focus on the measurement of strain, but systems have also been used for temperature measurements [5]. Optical temperature sensors possess some unique advantages over conventional electrical and acoustic temperature sensors, e.g., high sensitivity, compact size, immunity to electromagnetic interface and harsh corrosive environment, and reliable measurements can be made at elevated temperatures [6]. A traditional pressure sensor has very limited usage in heavy industrial environments, particularly in explosive or electromagnetically noisy environments. Utilization of optics in these environments eliminates all surrounding influences [7]. Sensing with an optical fiber Bragg grating is based on the variation of the Bragg wavelength. In many instances, the change on the Bragg wavelength is strongly dependent on the external "potential" such as temperature or strain. Temperature has the effect of altering their refractive index of both the core and the cladding of the fiber, as well as altering its length [8].

This paper discussed the LCFBG based sensors. LCFBG is used as direct sensing elements for strain, pressure and temperature. Effect of change of strain, pressure and temperature on Bragg wavelength and grating period is also investigated. The applied strain with temperature that compensates the thermal effect reaching to Bragg wavelength compensation is also discussed and obtains zero shift of Bragg wavelength

2. MATHEMATICAL MODEL

A. Principle of LCFBG sensors

A chirped FBG has a Bragg condition, λ_B which varies as a function of position along the grating. This is achieved by ensuring that the periodicity, Λ, varies as a function of position, or that the mode index, n_{eff} varies as a function of position along the FBG [9, 10], or through a combination of both. The Bragg condition for the chirp FBGs can be written as in equation (1).

$$\lambda_B(z) = 2n_{eff}(z)\Lambda_B(z) \tag{1}$$

,where z is the position along the grating. Each position has its' own resonance condition and reflects its own wavelength. This can also be interpreted as each wavelength having a different reflection point along the grating. The linearly chirp FBG's is shown in Fig. 1.

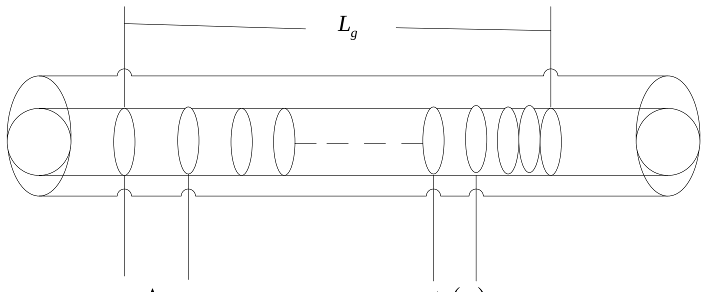

Fig. 1: Linearly chirped Bragg grating where periodicity Λ, varies as a function of position z.

In a linearly periodic chirped FBG, the dependence of the period of the refractive modulation upon the axial position along the FBG can be expressed as [11];

$$\Lambda(z) = \Lambda_0 + \frac{(\Lambda_{lg} - \Lambda_0)}{l_g} z \tag{2}$$

,where Λ_o is the period at the start of the grating, Λ_{lg} is the period at the end of the grating and l_g is the grating length. This provides a varying Bragg condition along the length of the grating. There reflectivity at the Bragg wavelength can be estimated using the reflection coefficient, $r = |\rho^2|$ where ρ is the reflectivity coefficient can be written as following.

$$\rho = \frac{-\kappa \sinh\left(\sqrt{\gamma L_g}\right)}{\hat{\sigma} \sinh\left(\sqrt{\gamma L_g}\right) + i\gamma \cosh\left(\sqrt{\gamma L_g}\right)} \tag{3}$$

,where $\gamma = \kappa^2 - \hat{\sigma}^2$

$\hat{\sigma}$ = general 'dc' self coupling coefficient and κ = "ac" coupling coefficient defines as

$$\kappa(z) = \frac{\pi}{\lambda_B} \frac{\Delta n}{n_{eff}} \tag{4}$$

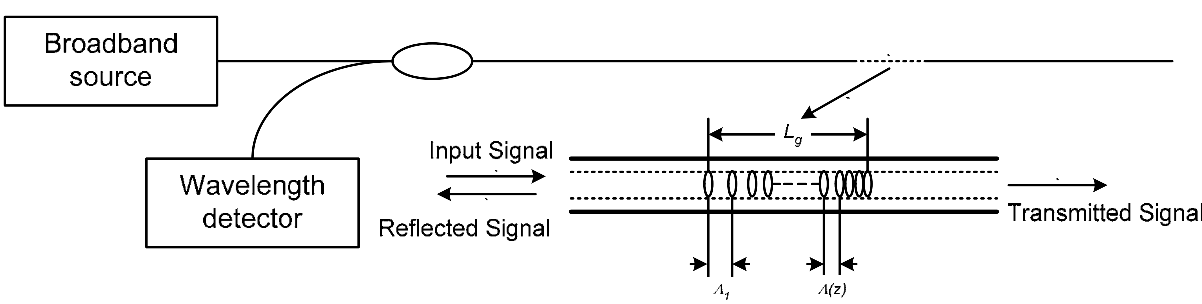

Fig. 2: LCFBG based sensor system with reflection detection.

To understand how the FBG may be used for sensing, the Bragg reflection wavelength is considered. Any change in fiber properties, such as strain, pressure or temperature which varies the modal index or grating pitch, will change the Bragg wavelength. Bragg reflection wavelength has being dependent on an external parameter to be sensed, which is designated as *X*. Here *X* can be temperature, *T* or strain ε or pressure *P*. The wavelength, which is determined by the Bragg condition, gets reflected at the Bragg grating part and the other wavelengths pass through it. Fig. 2 shows this process. The Bragg condition is expressed as equation (5), the reflected wavelength λ_B, called the Bragg wavelength, is defined by the relationship given in equation (5).

$$\lambda_B = 2n_{eff}\Lambda \tag{5}$$

,where Λ is the grating period and n_{eff} is the grating effective refractive index. The functional dependence of the Bragg wavelength on thermal and strain parameters can be calculated as

$$\begin{aligned}\frac{d\lambda_B}{dX} &= 2\frac{d}{dX}\left(n_{eff}\Lambda\right) = 2\Lambda\frac{dn_{eff}}{dX} + 2n_{eff}\frac{d\Lambda}{dX} \\ &= 2\Lambda\partial n_{eff} + 2n_{eff}\Lambda\alpha\end{aligned} \tag{6}$$

$$\frac{1}{\lambda_B}\frac{d\lambda_B}{dX} = \frac{2\Lambda\partial n_{neff}}{2n_{eff}\Lambda} + \frac{2n_{eff}\Lambda\alpha}{2n_{eff}\Lambda} = \frac{\partial n_{eff}}{n_{eff}} + \alpha \tag{7}$$

$$\Delta\lambda_B = \frac{d\lambda_B}{dX}\Delta X = \lambda_B\left(\frac{\partial n_{eff}}{n_{eff}} + \alpha\right)\Delta X \tag{8}$$

,where $\frac{\partial n_{eff}}{n_{eff}}$ is the normalized sensitivity of the effective index of the mode, and α is the coefficient of physical length change dependent on the parameter *X*. $\Delta\lambda_B$ is the shift in the Bragg grating center wavelength due to temperature or strain change.

B. Temperature sensing with LCFBG

The temperature sensitivity of a FBG is primarily due to the thermo optic effect. Under the influence of temperature, the modulation of the FBG parameter changes the resonance condition and thus produces a shift in Bragg wavelength. The shift, $\Delta\lambda_{BT}$, in the Bragg grating center wavelength due to temperature changes can easily be calculated

$$\Delta\lambda_{BT} = 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{9}$$

,where $\Delta T = (T-T_0)$, *T* is the heating temperature and T_0 is a reference temperature. Temperature measured in ^{0}C. Equation (9) can be written as in equation (10).

$$\Delta\lambda_{BT} = \lambda_B\left(\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T} + \alpha_\Lambda\right)\Delta T \tag{10}$$

,where $\alpha_\Lambda = \frac{1}{\Lambda}\frac{\partial n_{eff}}{\partial T}$,where λ_B is the fiber Bragg grating center wavelength on at *T*, α_Λ is the thermal expansion coefficient and $\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T}$ is the thermo-optical coefficient of the FBG.

C. Strain sensing with LCFBG

Strain shifts the Bragg wavelength through dilating or compressing the grating and changing the effective index. The strain response arises due to both the physical elongation of the sensor and corresponding fractional change in grating pitch, and the change in fiber index due to photo elastic effects. The amount of shift in the Bragg wavelength $\Delta\lambda_{BS}$ due to strain changes can be achieved by equation (11).

$$\Delta\lambda_{BS} = \lambda_B(1-\rho_a)\Delta\varepsilon \quad (11)$$

,where ρ_a is the stress-optic coefficient as in equation (12) and $\Delta\varepsilon$ is applied strain.

$$\rho_a = \frac{n_{eff}^2}{2}\left[\rho_{21} - \sigma(\rho_{11} - \rho_{12})\right] \quad (12)$$

,where ρ_{11} and ρ_{12} are coefficients of the stress-optic sensor, and σ is Poisson's ratio.

D. Zero shift calculation

The strain response arises from both the physical elongation of the gratings, thus the corresponding change in Λ, and form the change in the mode refractive index due to the photo-elastic effect. The thermal response arises from the thermal expansion of the fiber material and the temperature dependence of the mode refractive index, which is called thermo-optic effect. Under the influence of strain and temperature, the sensor responds via a shift in the Bragg wavelength, $\Delta\lambda_B$.

$$\Delta\lambda_B = \Delta\lambda_{BT} + \Delta\lambda_{BS} \quad (13)$$

From equation (8) and (10), equation (13) can be written as in equation (14).

$$\Delta\lambda_B = \left(\lambda_B\left(\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T} + \alpha_\Lambda\right)\Delta T\right) + \left(\lambda_B(1-\rho_a)\Delta\varepsilon\right) \quad (14)$$

The applied strain with temperature can compensate the temperature effect reaching to a Bragg wavelength compensation, $\Delta\lambda_B = 0$. To obtain zero shifts in Bragg wavelength, which is by setting, $\Delta\lambda_B = 0$, equation (14) can be writing as in equation (15).

$$\left(\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T} + \alpha_\Lambda\right)\Delta T = -(1-\rho_a)\Delta\varepsilon \quad (15)$$

$$\Delta T = \frac{-(1-\rho_a)}{\left(\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T} + \alpha_\Lambda\right)}\Delta\varepsilon \quad (16)$$

It is shown that the applied strain can be used as a compensator to shift the Bragg wavelength.

E. Pressure sensing with LCFBG

For a pressure change, ΔP, the corresponding shift in $\Delta\lambda_{BP}$ is given by :

$$\frac{\Delta\lambda_{BP}}{\lambda_B} = \frac{\Delta(n_{eff}\Lambda)}{n_{eff}\Lambda} = \left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial P} + \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial P}\right)\Delta P \quad (17)$$

The changes in physical length and refractive index are given by [18]

$$\frac{\Delta L}{L} = -\frac{(1-2\sigma)P}{E} \quad (18a)$$

$$\frac{\Delta n_{eff}}{n_{eff}} = \frac{n_{eff}^2 P}{2E}(1-2\sigma)(2\rho_{21} + \rho_{11}) \quad (18b)$$

,where E is Young's modulus of the fiber. As a result of $\Delta L/L = \Delta\Lambda/\Lambda$ then normalized pitch-pressure and the index-pressure coefficients are given by

$$\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial P} = 1\frac{1-2\sigma}{E} \quad (19a)$$

$$\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial P}=\frac{n_{eff}^2}{2E}(1-2\sigma)(2\rho_{21}+\rho_{11}) \quad (19b)$$

By substituting equations (19a) and (19b) into (17), we obtain the wavelength–pressure sensitivity, given by

$$\Delta\lambda_{BP}=\lambda_B\left[-\frac{(1-2\sigma)}{E}+\frac{n_{eff}^2}{2E}(1-2\sigma)(2\rho_{12}+\rho_{11})\right]\Delta P \quad (20)$$

,where *E* is the Young's modulus of the elasticity of the fiber (=72 GPa). For normal silica fibers, the center of FBG wavelength is 1550 nm and *n* =1.482.

3. RESULTS AND DISCUSSIONS

The exact value of thermal and strain response depends on the composition of the fiber is used. In this case silicon based fiber is considered. Numerical simulation will be carried out by MATLAB software for the developed model.

As the Bragg wavelength is represented by, $\lambda_B = 2n_{eff}\Lambda$. Here grating period Λ is varied linearly then the Bragg wavelength λ_B also varied, as shown in Fig. 3, where different wavelength is reflected from different length of grating period.

The effect of temperature is constant for room temperature to 200 ^{0}C, but increases at the high temperature. Fig. 4 shows the change in Bragg wavelength as a function of temperature change. It is found that Bragg wavelength changes linearly as the change of temperature. As a change of temperature of 5 ^{0}C, the change in Bragg wavelength is about 0.07 nm. The grating period of the FGB changes linearly as the temperature changes which shows in Fig. 5. It is found that grating period increases 0.02 nm per 5 ^{0}C temperature change.

For a typical silica fiber is used, for which the effective strain optic constant is ρ_a = 0.22., and core refractive index is n_{eff} = 1.482. Bragg wavelength change as a function of applied strain is plotted in Fig. 6. It is observed that Bragg wavelength changes 0.18 nm as applied strain changes 10^{-4}. Fig. 7 shows the variation of grating period as the applied strain changes. It is found that grating length changes 0.04 nm as applied strain changes 10^{-4}.

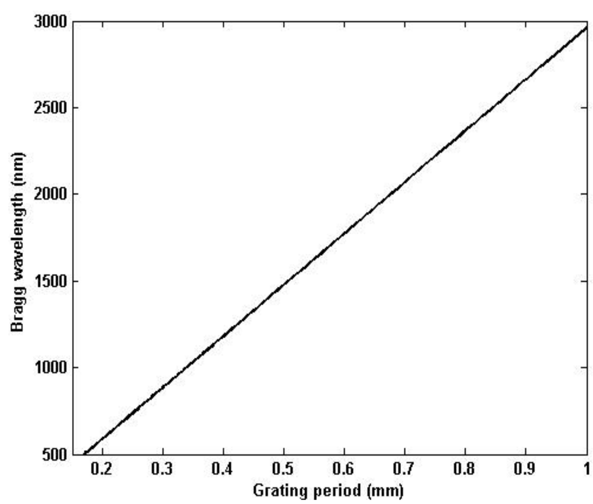

Fig. 3: Linearly chirped grating period versus Bragg wavelength.

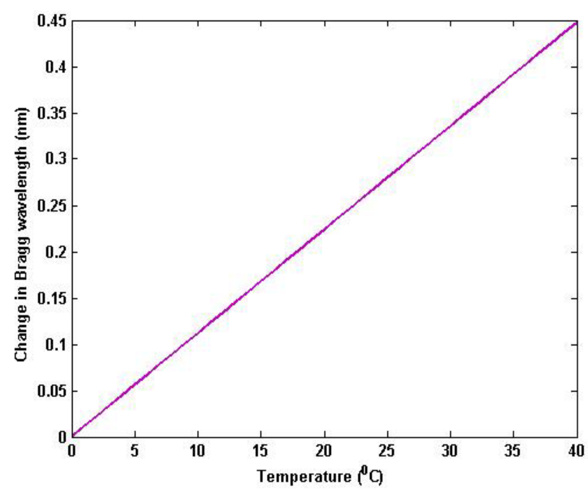

Fig. 4: Bragg wavelength shift as a function of temperature.

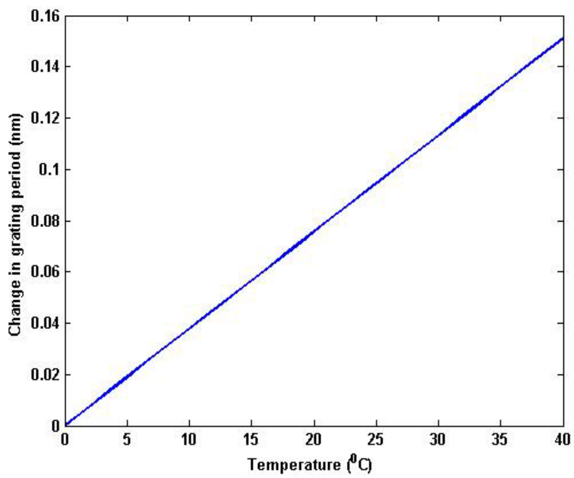

Fig. 5: Change in grating period as a function of temperature.

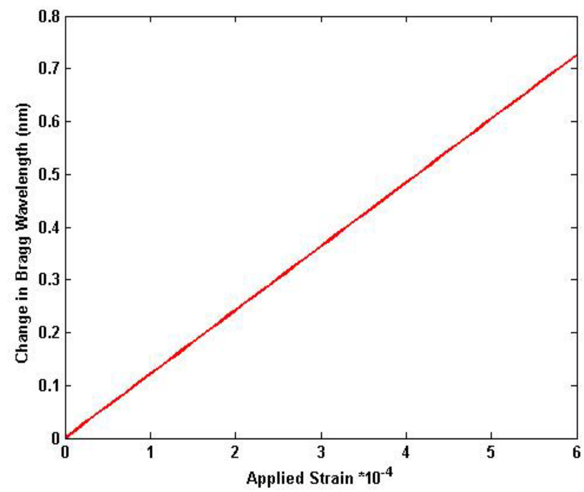

Fig. 6: Bragg wavelength shift as a function of applied strain.

Fig. 8 displays the applied strain that compensates the temperature effect reaching to a Bragg wavelength zero shift, $\Delta\lambda_B = 0$. The strain response is temperature dependent, but remain constant from room temperature to around 500 ^{0}C. Here we consider high temperature change and observed that by applying negative strain we can compensate temperature effect and vice versa.

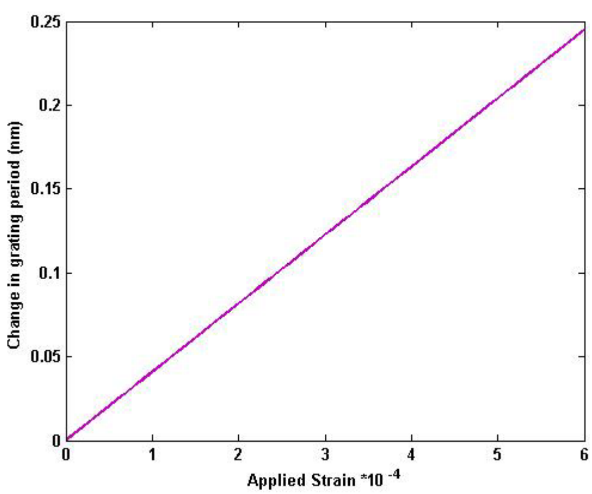

Fig. 7: Change in grating period as a function of applied strain.

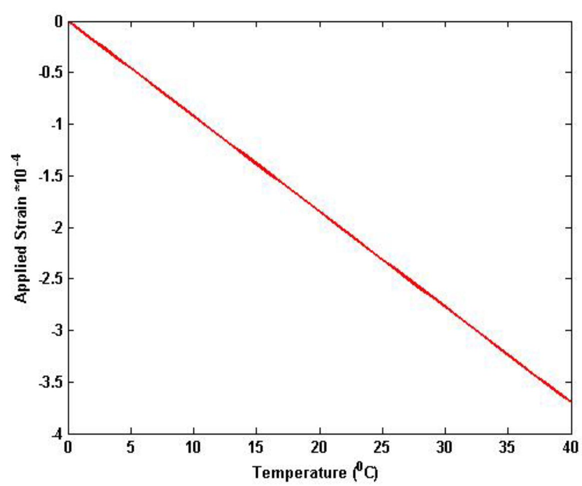

Fig. 8: The Change of the applied strain with the temperature to obtain a zero shift.

For a typical silica fiber is used, for which ρ_{11} = 0.113, ρ_{12} = 0.252, σ= 0.16, and n_{eff} = 1.482 Bragg wavelength change as a function of applied pressure is plotted in Fig. 9. It is observed that Bragg wavelength changes 0.15 nm as applied pressure changes 28 MPa. Fig. 10 shows the variation of grating period as the applied pressure changes. It is found that grating length changes 0.055 nm as applied pressure changes 30 MPa.

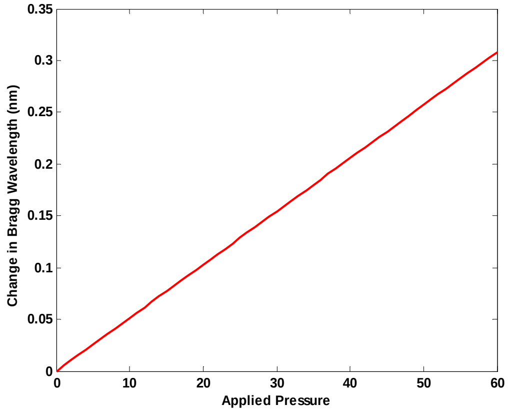

Fig. 9: Bragg wavelength shift as a function of applied pressure

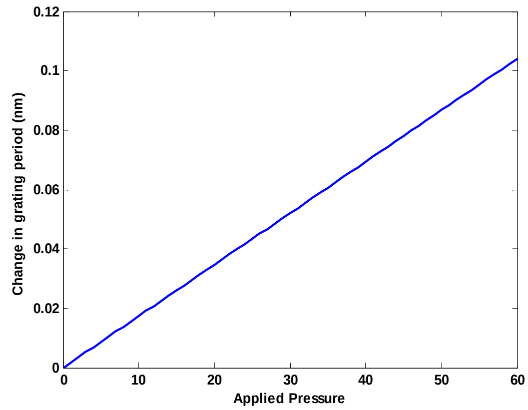

Fig. 10: Change in grating period as a function of applied strain.

4. CONCLUSIONS

It is very important to develop reliable sensors for accurate and reliable measurement of temperature, strain and pressure for safe and efficient operation and control for various industrial applications. In this paper the thermal, pressure and strain optical fiber grating sensors is investigated, using LCFBGs. A very important advantage of an LCFBG sensor is that it is wavelength-encoded. It is observed that Bragg wavelength as well as grating length of LCFBG varies linearly as change of temperature, pressure or strain. The compensation of the Bragg wavelength shift for the Bragg grating is studied and investigated. It is shown that the applied strain can be used as a compensator to the shift in Bragg wavelength and obtain zero shift.

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