Monitoring Thermal Effect in Femtosecond Laser Interaction With Glass by Fiber Bragg Grating

Chao Chen, Yong-Sen Yu, Rui Yang, Lei Wang, Jing-Chun Guo, Qi-Dai Chen, and Hong-Bo Sun

***Abstract*—Measurement of the local temperature in transparent materials irradiated by femtosecond laser pulses is important for deep insight into light–matter interaction physics and for proper laser micronanomachining, which is, however, technically challenging. We solve the problem in this paper by using a femtosecond laser-written fiber Bragg grating that can stably work up to 1000°C as a high-sensitivity temperature sensor to monitor the thermal effect. The peak temperature of the thermal impulse is estimated as around 4800 °C, which decays to around 500°C in the pulse interval for irradiation of 1.1 mJ under repetition rate of 1 kHz under 40 mm lens focusing.**

***Index Terms*—Femtosecond (fs) laser, fiber Bragg grating (FBG), light–matter interaction, optical fiber sensors.**

I. Introduction

FEMTOSECOND (fs) lasers are being utilized for advanced processing of materials and fabrication of functional devices in micro-optics [1], [2], micromachine [3], [4], microelectronics [5], and microfluidics [6], [7] due to their unique 3-D high-precision prototyping capability. When an fs laser beam is tightly focused inside a transparent medium, the light intensity at the focal volume may become sufficiently high to cause nonlinear absorption of the laser energy. The absorption is considered as launched by multiphoton absorption, which provides seed electrons for ensuing avalanche ionization, forming highly excited and spatially localized plasma and finally releasing energy by means of microexplosion [8]. In this scenario, the thermal effect at the laser excitation stage of light–matter interaction is largely excluded because photon energy is deposited into materials at a time scale much shorter than it could be transferred to surrounding lattice by means of phonon emission. The fs laser nanofabrication is, therefore, called cold machining, whereby it is established as a promising tool for processing brittle, rigid, or soft materials that are difficult to mechanically machine [9]. However, it has been recently noticed that thermal effect is not negligible, and it even plays a critical role if high fabrication precision is pursued. For example, Eaton *et al.* [10] ascribed the waveguide formation in glass by low-laser pulse energy irradiation at high repetition rate to heat accumulation effect. In most cases, the thermal effect is thought of detrimental, causing the difficulty in local control of the refractive index variation and precise definition of voxels shape [10], [11]. In order to elucidate the role played by thermal effect, direct *in situ* temperature measurement would be of great help. This is, however, technically challenging due to the small volume of the focal spot and the ultrafast feature of light–matter interactions. To solve this problem, we utilize in this paper a fiber Bragg grating (FBG) to monitor the temperature rise at the nearby site of fs laser irradiation in the same glass fiber. Due to the sensitive dependence of FBG resonance, wavelength on local temperature, the thermal impulse peak values under varied laser pulse energies and repetition rates are attained.

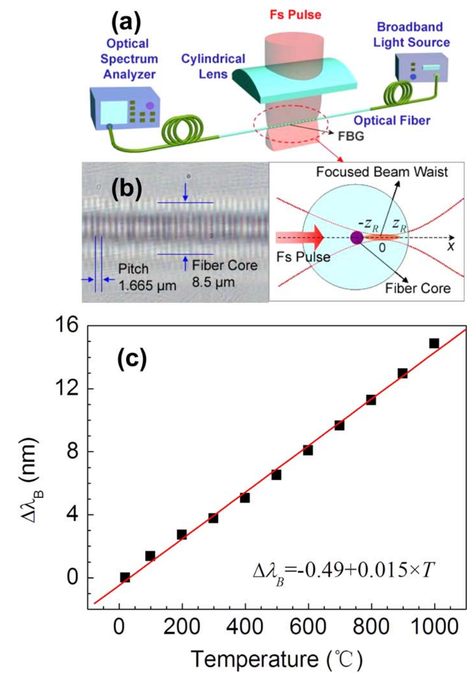

Fig. 1. (a) Experimental layout for monitoring the thermal effect. (b) Microscope image of the grating structure. (c) Isochronal annealing results for the fs robust FBG.

II. Experiments

Fig. 1(a) illustrates the experimental layout of the heat measurement. The capability of high-temperature sensing is critical for the system proper functioning. The conventional photosensitive grating structures of FBG sensors created by photorefraction under ultraviolet exposure stably work under 400°C [12], which cannot fulfill the desired task. To solve this problem, we fabricated FBG with permanent refractive index change in

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telecom SMF-28 silica fiber using near-infrared fs laser irradiation under a phase mask [13], [14]. Experimentally, a Ti: sapphire regenerative amplifier laser system with the operation wavelength of $\lambda_{\rm in} = 800$ nm and 100 fs pulse duration was chosen. The 4 mm radius ω_0 laser beam with 0.7 mJ pulse energy at 100 Hz repetition rate was focused into the fiber sample via a cylindrical lens with a focal length of $f = 40$ mm, passing through a mask of $\Lambda_{\rm PM} = 3.33$ μm pitch, positioned 3 mm away from the fiber. An FBG [see Fig. 1(b)] with grating length $L = 6.0$ mm and reflectivity $R = 99\%$ was attained after 16 s exposure. The intensity threshold value of grating formation in the fiber is approximately 10^{13} W/cm^2. The resonance wavelength λ_B is decided by $m\lambda_B = 2n_{\rm eff}\Lambda_G$, where m is the order number, $n_{\rm eff}$ is the effective refractive index of fiber grating, and the grating pitch is $\Lambda_G = \Lambda_{\rm PM}/2$. The thermal stability of the FBG was tested by isochronal annealing (1 h) in a heating furnace with temperature rise from room temperature to above 1000 °C [15], [16]. Two ends of the FBG were connected to a broadband light source and an optical spectrum analyzer (OSA, AQ6370B, Yokogawa) to record the transmission spectra. The spectral shape was on the whole kept unchanged in the entire course of annealing, while the peak gradually moved to longer wavelength and returned to the original position after the temperature fell to the room temperature. For the temperature calibration, a linear dependence [see Fig. 1(c)] of the Bragg resonance wavelength shift $\Delta\lambda_B$ was found [see Fig. 1(c)], $\Delta\lambda_B = 0.015T - 0.49$. The temperature-detecting sensitivity is, therefore, 15 pm/°C. Such an FBG sensor is well suited for calibrating the temperature effect in fs laser interaction with the silica material consisting of the fiber.

The photons are absorbed by materials within the pulse lasting duration, while part of the deposited energy was finally transferred from electrons to the surrounding lattice through electron–phonon coupling in picosecond duration as described by the dual-temperature model [17]. Thermal effect produced by this means is inevitable, and a spatially localized thermal impulse is formed. The transient temperature rise is difficult to experimentally gauge, but the average amount of the total thermal release from each pulse is measurable provided that the excitation process is spatially and temporarily integrated. For spatial integration, the laser beam was focused with a cylindrical lens so that the laser pulse energy is spread to the region near the FBG [see Fig. 1(b)]. The directional axial thermal diffusion is, therefore, negligible and thermal conduction occurs only radially. Since the heating point (the thermal source) is not located exactly at the fiber core center, although very near to it, usage of cylindrical coordinates is not more convenient than Cartesian ones. We choose Cartesian coordinates for the calculation. The model is described by

$$\frac{\partial T(x,t)}{\partial t} = \frac{\kappa}{\rho c}\frac{\partial^2 T(x,t)}{\partial x^2} + \frac{Q_{\rm net}}{\rho c} \qquad (1)$$

where $T(x,t)$ is the temperature at the position x away from the focal center at time t, ρ is the material density, and κ and c are the heat conductivity and the specific heat capacity, respectively. It should be noted that, ρ, κ, and c are related to temperature. They were adopted in the calculation of room-temperature values since the accurate values at high temperatures are not all available. $Q_{\rm net}$ is the net energy absorbed by the material in a volume of V exposed to laser pulse, and $Q_{\rm net} = \alpha E_{\rm in}/V$, where α is the absorption coefficient, dependent on input intensity $E_{\rm in}$. For time integration, repetitive irradiation with equal time interval was used to heat the fiber, whereby a stable equilibrium temperature $T_{\rm eq}$ is built when the heating efficiency equals the heat dissipation. $T_{\rm eq}$ is associated with $\Delta\lambda_B$ according to

$$T_{\rm eq} = \frac{\int_0^\tau \int_0^D T(x,t)dxdt}{\tau D} \qquad (2)$$

where $D = 125$ μm is the fiber diameter and τ is the pulse interval. It is obvious that only if $T_{\rm eq}$ is measured, the total thermal release from each pulse is deducible.

It is worthy to point out that a proper distance from the laser focus to grating region in the fiber core was chosen to avoid grating structure damage. The distance was approximately one Rayleigh length z_R, as shown in Fig. 1(b). According to the Gaussian beam optics, the value of Rayleigh length for the focused beam is $z_R = \pi\omega/\lambda_{\rm in} \approx 26$ μm, where ω is the beam waist radius, $\omega = \lambda_{\rm in} f/(\pi\omega_0) \approx 2.5$ μm. The laser intensity at the position of Rayleigh length is $I(0, \pm z_R) = I_0/2$, where $I_0 = I(0,0)$ is the light intensity at the beam waist. The fiber grating structure would not be destroyed if the light intensity was below the threshold value $I(0, \pm z_R) < I_{\rm th}$, consequently avoiding the refractive index of fiber grating change again leading to the resonant wavelength shift. Of course, though the pulse energy intensity is not high enough to damage the grating structure, the instantaneously deposited high energy is able to excite the valence band electrons jumping to conduction band in fs time scale, and the process generates lots of conduction band electrons and valence band holes, namely free carriers, which can also help to change the refractive index. But the existence of free carriers is just an instantaneous effect because the heated electrons (conduction band electrons) will jump back to valence band and transfer their energy to lattice in ps time scale, which leads to lattice temperature increment. In our experiment, the maximum pulse repetition rate is 1 kHz, and then the minimum pulse interval is 1 ms, which is much longer than the free carriers' lifetime. Actually, only the thermal effect is dominant in the process and the resonant wavelength shift caused by free carriers is not within the time range of spectroscopic recording. In addition, the signal trigger delay time of the OSA is about 100 μs, and the whole spectrum scanning time is above 1 s. In this scheme, we can consider that the resonant wavelength shift in the laser exposure process is just due to the thermal effect rather than material refractive index change by fs laser.

III. Results and Discussions

Typical laser pulse repetition rate [see Fig. 2(a)] and laser pulse energy $E_{\rm in}$ [see Fig. 2(b)] dependent transmission spectra were recorded, from which the corresponding wavelength shift $\Delta\lambda_B$ is extracted (see Fig. 3). The laser repetition rate is ranged from 1 Hz to 1 kHz, and the pulse energy is limited under 1.1 mJ (measured at the output of the fs laser) to prevent fiber grating damage. This value can guarantee that at the core of the fiber light intensity goes under the threshold value of grating formation. Two facts are obtained from the aforementioned data. First, for fixed laser pulse energy, the wavelength shift is linearly dependent on the repetition rate [see Fig. 3(a)]. This means that

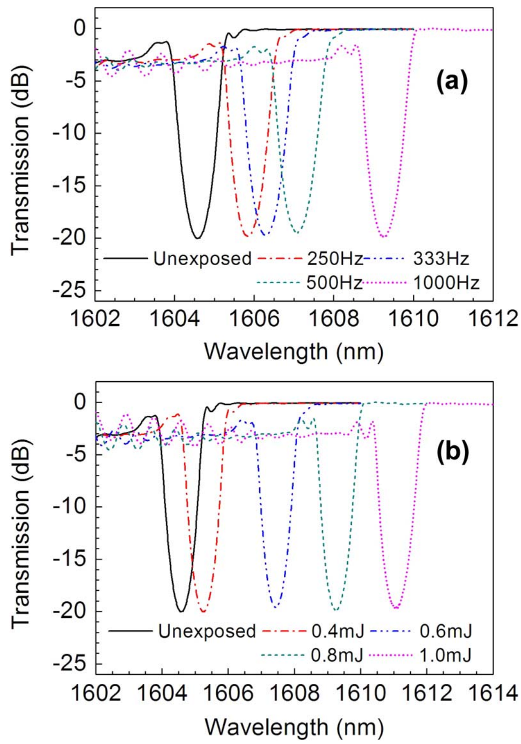

Fig. 2. (a) Spectra shift with different laser repetition rate at the pulse energy of 0.8 mJ. (b) Spectra shift with different laser pulse energy at the repetition rate of 1 kHz.

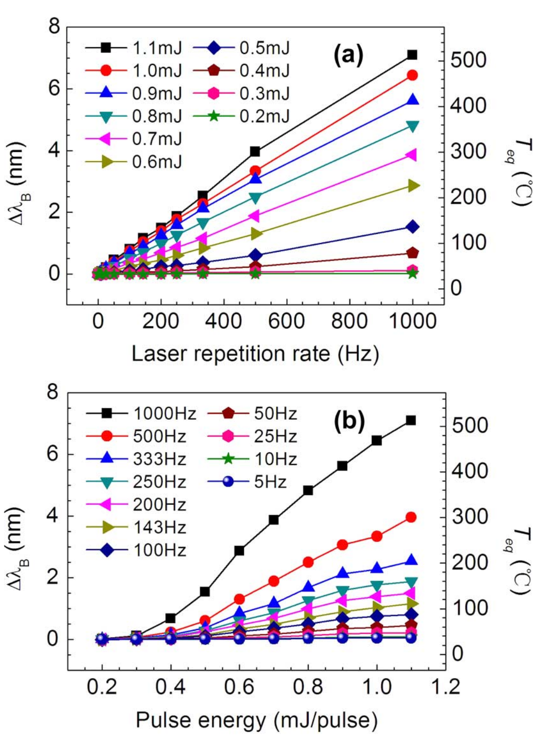

Fig. 3. (a) Bragg wavelength shift and equilibrium temperature increase with laser repetition rate at different pulse energy ranging from 0.2 to 1.1 mJ with increment of 0.1 mJ. (b) Bragg wavelength shift and equilibrium temperature increase with laser pulse energy at different repetition rate ranging from 5 Hz to 1 kHz.

reduction of the pulse interval helps the thermal accumulation from the sequential pulse shots, as elevated the equilibrium temperature as expected. Second, in contrast, $\Delta\lambda_B$ increases versus laser pulse energy in a nonlinear manner [see Fig. 3(b)]. It stays still at low pulse energy ($E_{\rm in} < 0.3$ mJ), implying negligible thermal accumulation in the grating region. With the increase of the laser pulse energy, $\Delta\lambda_B$ first rises and then tends to saturate, which is particularly pronounced at low repetition rates (< 300 Hz). The entire dependences are well fitted with a function of $\Delta\lambda_B \propto [1 + e^{(E_{\rm in}-E_0)/dE}]^{-1}$, where E_0 is the value of $E_{\rm in}$ at the inflection point, and dE is related to the reciprocal of the slope of the tangent at this point. The exponential dependence is consistent with the following physical picture of fs pulse excitation. The laser pulse energy increase leads to more electrons excited by the rising edge of a pulse to the conductive band through multiphoton ionization, and these seed electrons strongly absorb photons on the falling edge of the same pulse, resulting in avalanche ionization, and plasma is therefore formed. The higher the input pulse energy intensity, the more the seed electrons are generated, resulting in stronger absorption to the input energy and more intense excited plasma. The reduction of material heat capacity and heat conductivity versus temperature helps the thermal accumulation. On the other hand, the plasma formed from avalanche ionization defocuses the input laser pulse and ceases the increasing trend of absorption, and thus saturation tendency is achieved when the laser pulse energy is increased, as was experimentally observed by Streltsov and Borrelli [18].

Since both the furnace heating and laser pulse irradiation result in the same wavelength shift $\Delta\lambda_B$ in the monitoring fiber sensors, the local temperature of the grating region is directly calibrated. For example, irradiation under $E_{\rm in} = 1.1$ mJ at 500 Hz repetition rate produces a local temperature rise of 300 °C, equivalent to the case of irradiation under 0.7 mJ at 1 kHz. This suggests an isothermal plot [see solid line, Fig. 4(a)] showing local temperature under varied laser parameters: repetition rate not larger than 1 kHz and laser pulse energy lower than 1.1 mJ. A maximum local temperature of 500°C has been attained. Notice that the measured $T_{\rm eq}$ is a time and spatial average. With the assumption of Gaussian pulse shape in both domains, the peak value of the thermal impulses created at the irradiation transient can be estimated, for which the nonlinear absorption coefficients at different laser pulse energy were calculated. As shown in Fig. 4(b), we have $\alpha \sim 5\%$ for laser intensity of 2 J/cm^2 and $\alpha \sim 31\%$ for 6.4 J/cm^2 at pulse energy of 0.3 and 1.1 mJ, respectively. These values allow for an isothermal plot [see dashed line, Fig. 4(a)] determined fully by the thermal conduction model outlined by (1) and (2). It is found in good consistent with the experimental plot, proving the validity of the model. The maximum transient local temperature versus laser pulse energy is thus attainable [see Fig. 4(b)], which is found as large as 4800°C when irradiated with laser pulse energy of 1.1 mJ under repetition rate of 1 kHz. It should be noted that there were two important estimations made in the simulation. One was the parameters related to temperature were adopted values at the room temperature, which overestimates the temperature rise considering that the specific heat capacity increases versus temperature. The other was to set the temperature at the fiber surface and air boundary T_B to room temperature $T_{\rm RT}$, which underestimates the peak temperature by $T_B - T_{\rm RT}$. Since the

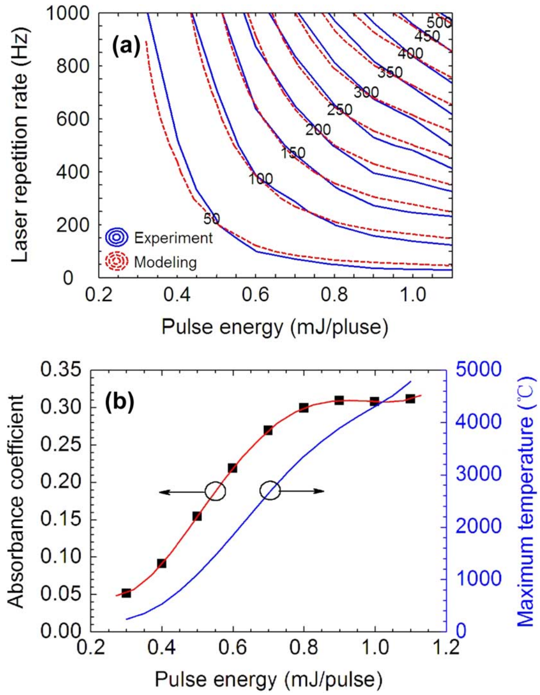

Fig. 4. (a) Isothermal curves of the equilibrium temperature in silica fiber by fs laser direct exposure with different pulse energy and repetition rate. The number on each curve denotes the corresponding equilibrium temperature. (b) Relationship between absorption coefficient and pulse energy (red) and the maximum transient local temperature versus laser pulse energy (blue) at the repetition rate of 1 kHz.

relative weight of the overestimation and the underestimation is unknown, we keep the result deduced from (2). Considering all these factors, we believe that the total error of the peak temperature estimation is about 20%.

Finally, the experiment to test the model by changing the location of the beam waist in fiber has also been conducted. The results are similar to the one described earlier only if the laser energy intensity is under the damage threshold of fiber core.

IV. Conclusion

We have proposed the use of fs laser-written FBG sensors that are able to work stably up to 1000 °C for monitoring the local thermal effect occurring upon fs laser interaction with glass consisting of the fiber. An average temperature of 500°C was measured for 1.1 mJ irradiation at repetition rate of 1 kHz, and the corresponding peak value of the thermal impulse is around 4800 °C.

References

[1] D. Wu, L. G. Niu, Q. D. Chen, R. Wang, and H. B. Sun, "High efficiency multilevel phase-type fractal zone plates," *Opt. Lett.*, vol. 33, pp. 2913–2915, Dec. 2008.

[2] Q. D. Chen, D. Wu, L. G. Niu, J. Wang, X. F. Lin, H. Xia, and H. B. Sun, "Phase lenses and mirrors created by laser micronanofabrication via two-photon photopolymerization," *Appl. Phys. Lett.*, vol. 91, pp. 171105-1–171105-3, Oct. 2007.

[3] S. Kawata, H. B. Sun, T. Tanka, and K. Takada, "Finer feature for functional microdevices," *Nature*, vol. 412, pp. 697–698, Aug. 2001.

[4] J. Wang, H. Xia, B. B. Xu, L. G. Niu, D. Wu, Q. D. Chen, and H. B. Sun, "Remote manipulation of micronanomachines containing magnetic nanoparticles," *Opt. Lett.*, vol. 24, pp. 581–583, Mar. 2009.

[5] Y. L. Zhang, L. Guo, S. Wei, Y. Y. He, H. Xia, Q. D. Chen, H. B. Sun, and F. S. Xiao, "Direct imprinting of microcircuits on graphene oxides film by femtosecond laser reduction," *Nano Today*, vol. 5, pp. 15–20, Jan. 2010.

[6] D. Wu, Q. D. Chen, L. G. Niu, J. N. Wang, J. Wang, R. Wang, H. Xia, and H. B. Sun, "Femtosecond laser rapid prototyping of nanoshells and suspending components towards microfluidic devices," *Lab Chip*, vol. 9, pp. 2391–2394, Jun. 2009.

[7] J. Wang, Y. He, H. Xia, L. G. Niu, R. Zhang, Q. D. Chen, Y. L. Zhang, Y. F. Li, S. J. Zeng, J. H. Qin, B. C. Lin, and H. B. Sun, "Embellishment of microfluidic devices via femtosecond laser micronanofabrication for chip functionalization," *Lab Chip*, vol. 10, pp. 1993–1996, Aug. 2010.

[8] E. N. Glezer and E. Mazur, "Ultrafast-laser driven micro-explosions in transparent materials," *Appl. Phys. Lett.*, vol. 71, pp. 882–884, Aug. 1997.

[9] R. R. Gattass and E. Mazur, "Femtosecond laser micromachining in transparent materials," *Nature Photon.*, vol. 2, pp. 219–225, Apr. 2008.

[10] S. M. Eaton, H. B. Zhang, P. R. Herman, F. Yoshino, L. Shah, J. Bovatsek, and A. Y. Arai, "Heat accumulation effects in femtosecond laser-written waveguides with variable repetition rate," *Opt. Exp.*, vol. 13, pp. 4708–4716, Jun. 2005.

[11] C. B. Schaffer, J. F. Garcia, and E. Mazur, "Bulk heating of transparent materials using a high-repetition-rate femtosecond laser," *Appl. Phys. A*, vol. 76, pp. 351–354, Oct. 2003.

[12] J. Rathje, M. Kristensen, and J. E. Pedersen, "Continuous anneal method for characterizing the thermal stability of ultraviolet Bragg gratings," *J. Appl. Phys.*, vol. 88, pp. 1050–1055, Jul. 2000.

[13] S. J. Mihailov, C. W. Smelser, D. Grobnic, R. B. Walker, P. Lu, H. M. Ding, and J. Unruh, "Bragg Gratings written in All-SiO_2 and Ge-doped core fibers with 800-nm femtosecond radiation," *J. Lightw. Technol.*, vol. 22, no. 1, pp. 94–100, Jan. 2004.

[14] J. Thomas, E. Wikszak, T. Clausnitzer, U. Fuchs, U. Zeitner, S. Nolte, and A. Tunnermann, "Inscription of fiber Bragg gratings with femtosecond pulses using a phase mask scanning technique," *Appl. Phys. A*, vol. 86, pp. 153–157, Feb. 2007.

[15] C. W. Smelser, S. J. Mihailov, and D. Grobnic, "Formation of type I-IR and type II-IR gratings with an ultrafast IR laser and a phase mask," *Opt. Exp.*, vol. 13, pp. 5377–5386, Jul. 2005.

[16] Y. H. Li, C. R. Liao, D. N. Wang, T. Sun, and K. T. V. Grattan, "Study of spectral and annealing properties of fiber Bragg gratings written in H_2-free and H_2-loaded fibers by use of femtosecond laser pulses," *Opt. Exp.*, vol. 16, pp. 21239–21247, Dec. 2008.

[17] J. G. Fujimoto, J. M. Liu, and E. P. Ippen, "Femtosecond laser interaction with metallic tungsten and nonequilibrium electron and lattice temperatures," *Phys. Rev. Lett.*, vol. 53, pp. 1837–1840, Nov. 1984.

[18] A. M. Streltsov and N. F. Borrelli, "Study of femtosecond-laser-written waveguides in glasses," *J. Opt. Soc. Am. B*, vol. 19, pp. 2496–2504, Oct. 2002.

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