A Highly Birefringent and Nonlinear $AsSe_2$-As_2S_5 Photonic Crystal Fiber with Two Zero-Dispersion Wavelengths

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Abstract: A hybrid $AsSe_2$-As_2S_5 photonic crystal fiber (PCF) with a solid elliptical core is proposed and studied theoretically by full-vector finite element method (FEM). The core and cladding of the PCF are made of $AsSe_2$ and As_2S_5 glasses, respectively. Simulation results demonstrates that, at the operating wavelength of 1.55 μm, the proposed PCF not only exhibits a very high birefringence of 0.091 but also has large nonlinear coefficients of 147.8 and 78.2 $W^{-1}m^{-1}$ for the X- and Y-polarized (X and Y-pol) modes, respectively. Moreover, it is able to achieve two zero-dispersion wavelengths (ZDWs) for both the X-pol (1.52 and 2.19 μm) and Y-pol (1.43 and 2.12 μm) modes. The proposed hybrid PCF exhibits excellent polarization maintaining and nonlinearity performance, thus suitable to be used in supercontinuum spectrum generation and polarization maintaining nonlinear signal processing.

Index Terms: High birefringence, nonlinearity, photonic crystal fiber, supercontinuum spectrum generation, zero-dispersion wavelength.

1. Introduction

Photonic crystal fibers (PCFs) have attracted much attention owning to their flexibility structure for the cross section and unique properties contrast to conventional fiber, such as tunable dispersion, high birefringence, and high nonlinearity [1–3]. Polarization maintaining and Super continuum generation are two widely developed applications of PCFs, which needs high birefringence and high nonlinearity. Compared to traditional birefringent fibers, PCFs can provide much higher birefringence by introducing asymmetry configuration due to the large index contrast. So far, many PCFs with high birefringence have been investigated theoretically [4–7] and realized experimentally [8, 9]. Some of them have attained birefringence up to an order of 10^{-2} by using elliptical air holes [6, 7]. However, simplified configurations with competitive properties are more desirable. In [10, 11], the authors designed hybrid PCFs that use circle air holes in the cladding and elliptical air holes in the core area to overcome the problem of poor mode confinement of the high birefringent PCFs. Since it is rather a challenge to realize multi-elliptical air holes in the core under current fabrication technology, simpler structure is desired.

Recently, soft glass (tellurite, chalcogenide, and fluoride) PCFs have been extensively investigated due to their large refractive index, high nonlinearity, and wide transparency in the near- and mid-IR region. In optical signal processing, supercontinuum generation and fibers sensor systems, many nonlinear effects are polarization sensitive. Therefore, polarization maintaining, tunable chromatic dispersion, and high nonlinearity PCFs based on soft glasses, particularly chalcogenide, are required for improving the performance of the nonlinear optics system. In particular, to generate an ultra-wide band supercontinuum spectrum, it is required to simultaneously present a high birefringence, large nonlinearity, and two zero-dispersion wavelengths (ZDWs) [12]. Various methods, such as preform drilling [13], stack and draw [14], and casting [15], were developed to fabricate chalcogenide glass PCFs and reduce their loss. Low loss chalcogenide

PCFs were realized in [16, 17], i.e. 13 dB/m at 1.55μm and 9 dB/m at 3.39 μm. Then the loss was further reduced to 1 dB/m in [15]. In [18], authors fabricated a solid core microstructured fiber based on $AsSe_2$ and As_2S_5, achieving a large nonlinear coefficient of 20.3 $W^{-1}m^{-1}$ at an operating wavelength 2 μm. M. Diouf et al. [19] proposed a PCF based on $AsSe_2$ with a high nonlinear coefficient of 1.2 $W^{-1}m^{-1}$ at the wavelength 3.9 μm, but it is difficult to realize two ZDWs regions. In [20], a simple silicon-core silica-cladding microfiber was proposed, having the nonlinear coefficients of 17.42 and 33.77 $W^{-1}m^{-1}$ of two orthogonal polarization modes at the operating wavelength 1.55 μm, respectively. However, it suffers from a high material loss. Thus, it is still a challenge to design a highly birefringent and nonlinear PCF with two ZDWs.

In this paper, a simple structure is proposed with all circular air holes in the cladding is made of As_2S_5 glass, and a solid elliptical core embedded in the central area of the PCF is made by $AsSe_2$ glass. This hybrid PCF (HPCF) could simultaneously achieve high birefringence, large nonlinear coefficient, and two ZDWs. Such a simple HPCF can be fabricated by using advanced fabrication technologies and its loss is mainly contributed by the absorption loss of the material itself. Commercial software COMSOL Multiphysics based on the full-vector finite element method (FEM) is adopted with the perfectly matched layer (PML) boundary condition to explore and analyse two orthogonally polarized fundamental modes with different structure parameters. The optical nonlinearity are calculated by analysing the effective mode area of the two fundamental modes. Birefringence, nonlinearity, and two ZDWs are attributed by the optimal structure parameters and materials. This design can find its use in nonlinear and polarization maintaining applications.

2. Configuration of the PCF

The configuration of the proposed PCF is shown in Fig. 1(a). The PCF has an elliptical core with the aspect ratio of R = *a*/*b*, where *a* and *b* are the diameters along the major and minor axis, respectively. A triangular lattice distribution of four air-hole rings defines its cladding. All the holes in the cladding have the same diameter *d* and the distance between two adjacent holes is Λ. A perfect matching layer with a thickness that is 10% of the whole diameter of the PCF is placed outside the cladding. The optimal values of the dimensions are *d* = 0.92 Λ, *a* = 0.4 Λ, and *b* = 0.8 Λ, where Λ= 0.7 μm. The reason that we set all the dimensions related to Λ is due to the scaling property of PCF reported in [21], i.e., one could scale its PCF design to other frequencies while maintaining its desirable performance.

The substrate materials (glasses) employed in the core and cladding are $AsSe_2$ and As_2S_5, respectively. The refractive indexes *n* of two materials plotted in Fig. 1(b) were calculated based on the Sellmeier equation of the novel chalcogenide glasses in [18]. The $AsSe_2$ and As_2S_5 glass rods can be attained by a direct synthesis from the elements with the purity of 99.99% at a temperature of 650°C in an evacuated silica ampoule [18]. The two glasses have good compatibility because of the fact that they have very similar thermal expansion coefficients, thus avoids the cracking at the core and cladding interface during the fiber drawing.

3. Characteristics of the PCF

The electric fields distribution of the X- and Y-pol modes at the wavelength 1.55 μm are shown in Fig. 2. According to Maxwells equations, the normal component of the electric flux density has to be continuous at the interfaces between $AsSe_2$ and As_2S_5, which leads to the discontinuous distribution of Y-pol mode, while the electric field distribution of X-pol mode is continuous.

The key performance characteristics of interest here include birefringence, nonlinear coefficient, dispersion, and loss. The birefringence is defined as B = $n_x - n_y$, where n_x and n_y represent the modal effective indices for the X and Y-pol modes, respectively. Nonlinearity of the PCF is an important factor to evaluate the nonlinear effects in short range fiber. An accurate estimation of nonlinear coefficient γ is needed to analyse the nonlinear effects, which can be calculated with

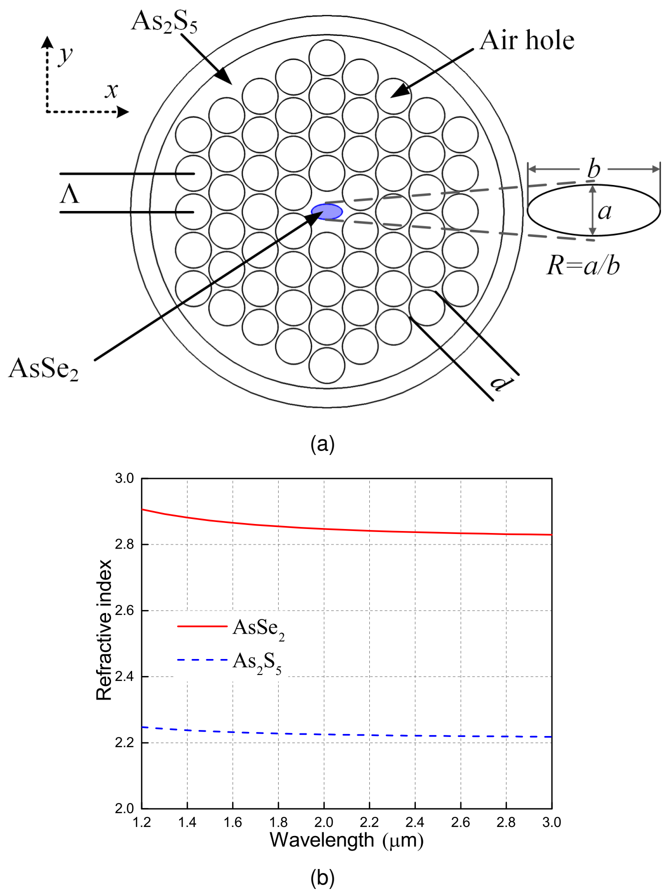

Fig. 1. (a) Configuration of the proposed PCF. (b) Material refractive index of $AsSe_2$ and As_2S_5 glasses.

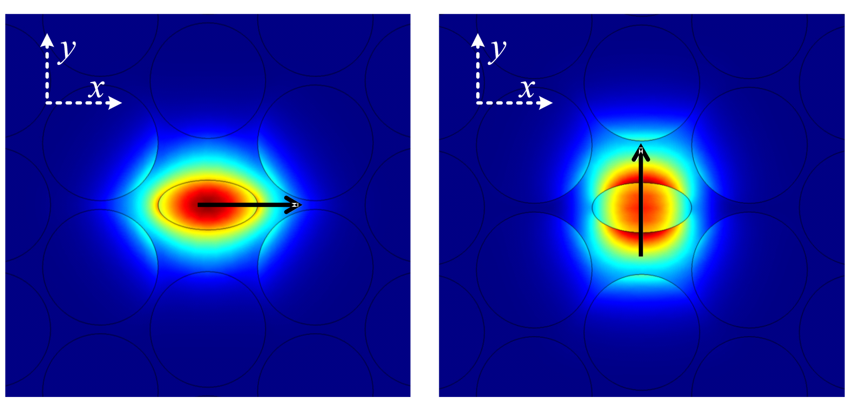

Fig. 2. (a) X and (b) Y-pol electric fields distribution of the proposed PCF.

the effective nonlinear interaction area according to [20].

$$\gamma = \frac{n_2 \omega_0}{c A_{eff}}, \tag{1}$$

where ω_0 is angular frequency, *c* is light velocity, n_2 = 1.1×10^{-17}m^{2}W^{-1} is the nonlinear index of the $AsSe_2$ glass, and A_{eff} is the effective nonlinear interaction area. Since the E-field distribution is discontinues at the interface of As_2S_5 and $AsSe_2$ glasses, the calculation of A_{eff} for basic modes should be modified considering [22].

$$A_{eff} = \frac{\mu_0}{\epsilon_0 n_{core}^2} \frac{|\iint_{D_{tot}} R_e\{E(x,y) \times H(x,y)\} \cdot e_z d_x d_y|^2}{\iint_{D_{inter}} |E(x,y)|^4 d_x d_y} \tag{2}$$

where e_z is the unit vector pointing to the positive *z* direction, E(x, y) and H(x, y) are the transverse components of the fundamental mode field, which can be calculated by FEM. The chromatic dispersion *D* is another key parameter of the PCF that can affect the performance of nonlinear application, e.g. supercontinuum generation. The nonlinear effects involved in the spectral broadening are highly dependent on the dispersion of the PCF and clever dispersion design can significantly reduce power requirements. *D* is determined by the second derivation of the effective refractive index as a function of the wavelength, which can be calculated by

$$D = -\frac{\lambda}{c} \frac{d^2 n_{eff}}{d\lambda^2}, \tag{3}$$

according to [1], where n_{eff} is the effective refractive index of the investigated mode. The loss property considered here contains confinement loss and material absorption loss. Due to the air filling ratio in the cladding is very high, the confinement loss is quite low [2], i.e. on the order 10^{-2} dB/m. The material absorption loss of the $AsSe_2$ glass is measured by the cut-back technique, which is about 1.2 dB/m around the wavelength of 3 μm [18]. Given these loss properties and considering the fact that only a very short length of PCF will be used in nonlinear applications, the loss of the proposed PCF is not discussed in the rest of this paper.

4. Simulated Performances of the PCF

Parameter sweeps were conducted to study how the size of the air holes in the cladding (d), the size of the elliptical core (a), and the aspect ratio of the elliptical core (R) affect the concerned performances. Based on the parameter sweep results, optimized dimensions of the PCF were obtained to attain high birefringence, large nonlinear coefficient, and two ZDWs simultaneously in the wavelength range from 1.2 to 2.2 μm.

4.1. Parameter sweep of diameter d

Diameter *d* of the air holes in the cladding determines the air filling ratio of the cladding, which affects the index contrast between the core and cladding. A parameter sweep of *d* was conducted by changing its value from 0.68 Λ to 0.92 Λ, while the other parameters were fixed at *a* = 0.4 Λ, Λ = 0.7 μm, and R = 0.5. The computed birefringence, nonlinear coefficient, and dispersion values are presented in Fig. 3.

A larger d leads to a higher air filling ratio in the cladding, thus results in a higher index contrast between the core and cladding and thereby more power is confined in the core. On one hand, this increases the birefringence because the birefringence is introduced by the elliptical core's different effects to the X and Y-pol modes. On the other hand, a better confinement in the core reduces A_{eff}, resulting in large nonlinear coefficients. The conclusions agree with the results shown in the left two subplots of Fig. 3. As observed in the right subplot of Fig. 3, increasing d lifts up the dispersion curves for both the two modes. When d = 0.92 Λ, two zero-dispersion wavelengths for both the X- and Y-pol modes are attained, which is highly appreciated by soliton self-compression for broadband supercontinuum generation [20]. As the parameter sweep results demonstrated, a larger d leads to better performances. However, it causes more difficulties in fabrication if d is too large. Therefore, in this work, the value of d is selected to be 0.92 Λ.

4.2. Parameter sweep of diameter a

With other parameters fixed at Λ = 0.7 μm, d = 0.92 Λ, and R = 0.5, parameter sweep of a was conducted as it determines the size of the core. Fig. 4 illustrates the birefringence, nonlinear

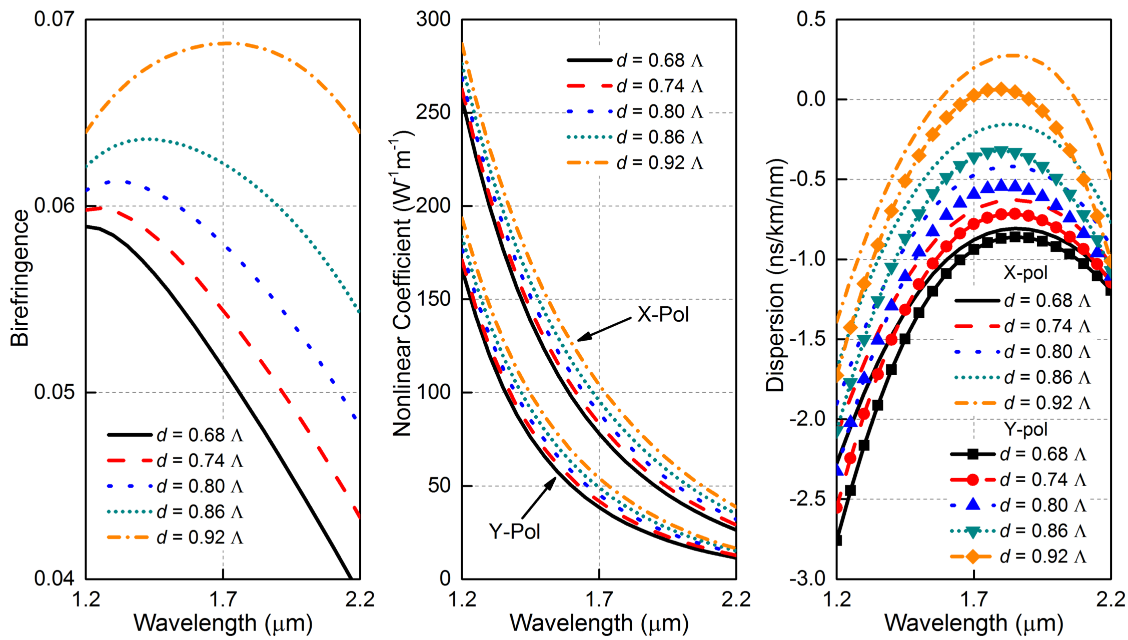

Fig. 3. Birefringence, nonlinear coefficient, and dispersion of the proposed PCF with different values of d across a wide bandwidth.

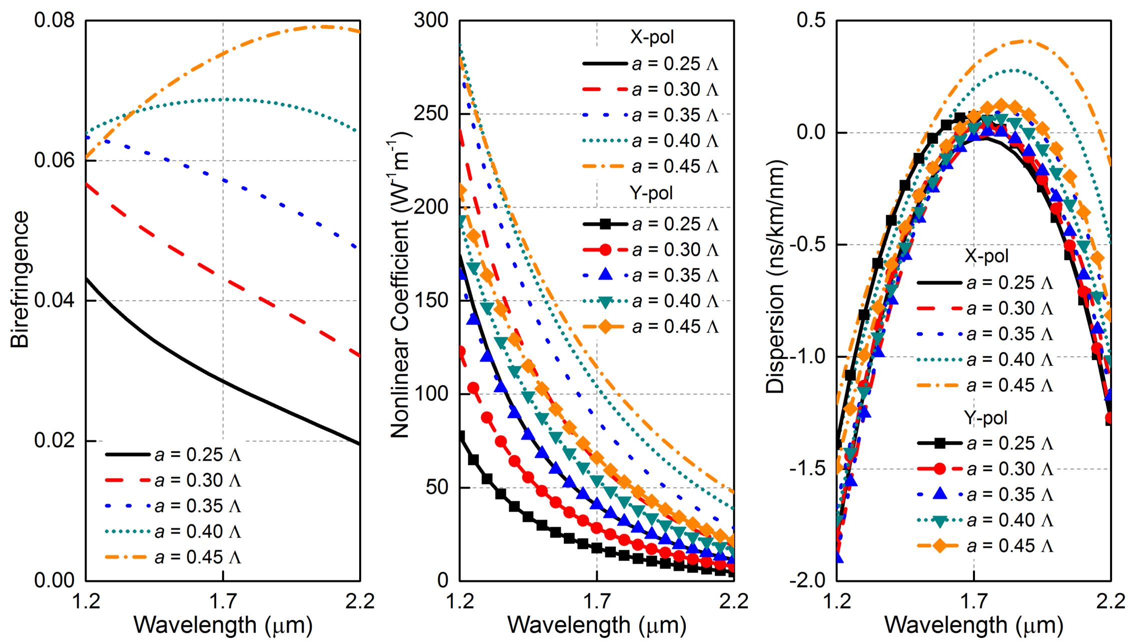

Fig. 4. Birefringence, nonlinear coefficient, and dispersion of the proposed PCF with different major diameter a of the elliptical core across a wide bandwidth.

coefficients, and dispersions of the PCF with different values of a.

Since the material of the core ($AsSe_2$) has a higher refractive index than the material of the cladding (As_2S_5), increasing the size of the core (a) improves the refractive index contrast between the core and cladding. Therefore, more power is confined in the core. For the same reason as

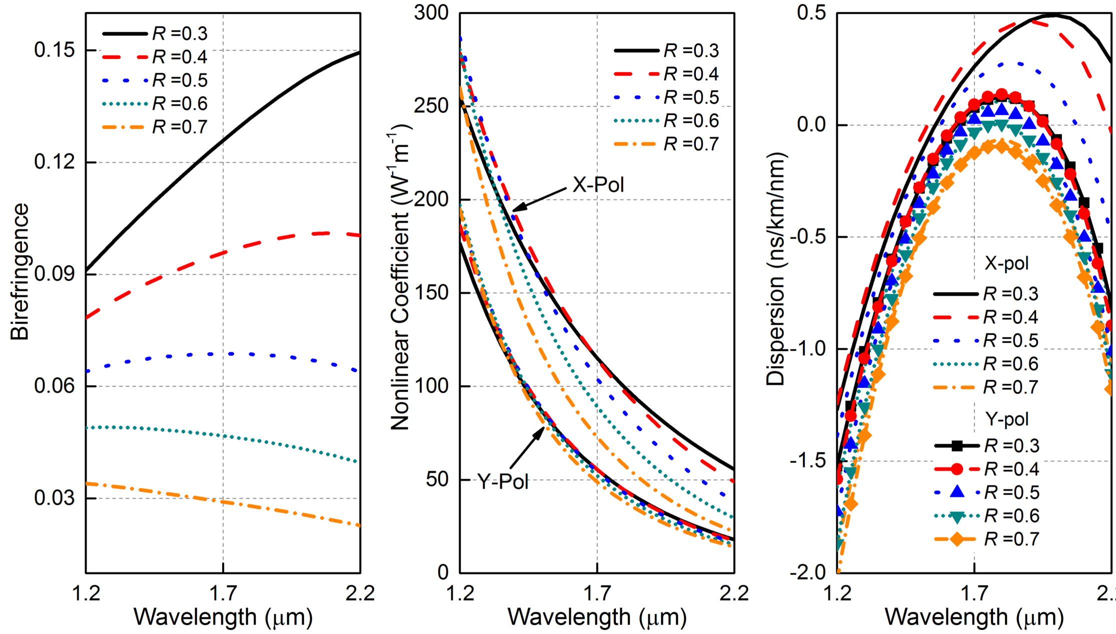

Fig. 5. Birefringence, nonlinear coefficient, and dispersion of the proposed PCF with different elliptical ratio R across a wide bandwidth.

described in the previous subsection, larger a leads to higher birefringence and higher nonlinear coefficients, which is validated from the simulation results shown in Fig. 4. Moreover, increasing a also increases the dispersion values, which enhances the interval between the two ZDWs. However, the size of the core has an upper limitation. If the core is too closed to the first ring of cladding, fabrication can be a big problem. To avoid fabrication failure while attaining best performance, a was selected to be 0.4 Λ in this work.

4.3. Parameter sweep of aspect ratio R

As discussed above, the birefringence is introduced by the elliptical core since it has different effects to the X and Y-pol modes. Therefore, the aspect ratio $R = a/b$ of the ellipse surely has some effects to the performance. A parameter sweep of R was conducted by changing the value of R from 0.3 to 0.7, while other parameters were fixed at a = 0.4 Λ, d = 0.92 Λ, and Λ = 0.7 μm.

As shown in the left subplot of Fig. 5, increasing R leads to a lower birefringence. This is expected because a larger R means the long axis and the short axis of the elliptical core is less different. For extreme case when R = 1, the core is a circle and the birefringence is zero.

During the parameter sweep, a is fixed and b decreases with the increase of R. This is equivalent to the core size for Y-pol mode remains unchanged and the core size for X-pol decreases. According to the conclusion from previous subsection, a larger core size leads to a larger refractive index, thereby a better confinement ability and larger nonlinear coefficients. Therefore, unchanged a (y-axis) and decreased b (x-axis) lead to the similar Y-pol nonlinear coefficients and reducing X-pol nonlinear coefficient, respectively, as shown in the middle plot of Fig. 5. Similarly, as shown in the right subplot of Fig. 5, the change in the dispersion values for X-pol is more significant than that for Y-pol. It can be concluded that a smaller R generally leads to better performances as concerned. However, the elliptical core will be more difficult to fabricate with a smaller R. Therefore, in this work, we chose R = 0.4. Note that higher birefringence and higher nonlinear coefficient for X-pol mode can be obtained if we chose a smaller R.

5. Conclusion

This paper presented a HPCF design that achieves high birefringence, large nonlinear coefficients for both X- and Y-pol modes, and two ZDWs characteristics in optical regime. The proposed fiber has a simple geometrical structure that is easy to fabricate. The superior performance comes from the high nonlinearities and large refractive index contrast of $AsSe_2$ and As_2S_5, which are employed as the core and cladding, respectively. Parameter sweeps of its key dimensions are conducted to attain the optimal performance and to provide insights for better understanding and guidelines for future designs. High birefringence, i.e., above 0.078, is achieved from 1.2 to 2.2 μm, along with large nonlinear coefficients, i.e. 147.8 and 78.2 $W^{-1}m^{-1}$ for X and Y-pol modes at the operating wavelength of 1.55 μm. The proposed PCF also exhibits two ZDWs for both X and Y-pol modes. The two ZDWs could be easily controlled by adjusting the structure parameters of the PCF. The proposed PCF has great potential in applications involving polarization dependent nonlinear optics, e.g., ultra-wide band supercontinuum spectrum generation and optical sensors [20].

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