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Optical Characterisations of Bi-Phosphosilicate Fiber for O Band Amplification

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Abstract: We report on the optical properties of Bi-doped phosphosilicate fiber. The fiber with a core and a clad diameter of 7.75 µm and 125 µm, respectively, is fabricated in-house using the modified chemical vapor deposition (MCVD) with in-situ solution doping technique. The spectroscopic properties of the fabricated fiber are characterized in terms of absorption, emission and lifetime. The lifetime decay is measured to be 800 µs; indicating a good potential optical amplification in the range of 1300 to 1500 nm. A Bismuth-doped fiber amplifier (BDFA) operating within the O-band region was successfully demonstrated. At 1340 nm, a 14.8 dB gain is achieved with 300 mW pumping power.

Keywords: Bismuth-doped fiber; MCVD; in-situ solution doping

1. Introduction

In recent years, a great deal of attention has been paid to Bismuth-doped fiber (BDF) as a new gain medium for optical amplifiers. The wide luminescence spectral range of BDF can be utilized to fill in the gap between 1260–1530 nm where no efficient rare-earth doped fiber amplifier exists [1]. The development of fiber amplifiers that can operate in the O-band region (1260–1360 nm) is important since silica fibers exhibit zero dispersion characteristics in that region. Due to this, optical amplifiers in the O-band region can potentially increase the transmission capacity for fiber optic communication systems [2]. A silica-based BDF amplifier operating at 1300 nm region exhibits number of advantages such as a broad amplification band with high efficiency [2]. At present, a 1300nm optical amplifiers using Praseodymium-doped fibers are fluoride-based, which are brittle and less robust, to be spliced with existing standard silica fibers [3].

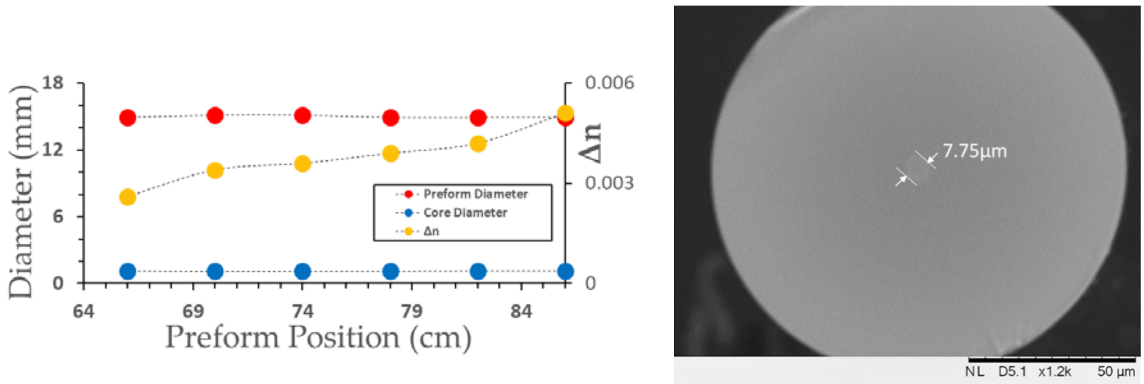
The first Bi fibers co-doped with alumina were fabricated using modified chemical vapour deposition (MCVD) in 2005 [4]. A 200 nm emission bandwidth in the 1100 nm region was demonstrated. Since then, the near-IR luminescence has been observed and investigated in many BDF glasses of various compositions. For instance, co-doping with germanium and phosphorus shifts the luminescence to the 1300–1500 nm region [1,5,6]. In addition, highly germanium doped Bi fibers have shown luminescence spectra up to 1800nm [5], while with low germanium content, the luminescence occurs in the telecom S-band covering from 1460 nm to 1530 nm [6]. A Bi fiber co-doped with phosphorus (commonly referred to as Bismuth phosphosilicate fiber) is significant, as the emission wavelength region coincides with the O-band window [2].

Although BDF exhibits a broad luminescence in the near-IR region, the unsaturable loss (UL) and excited state absorption (ESA) limit the available gain [7]. Various approaches have been put forward to overcome these problems including the use of different pump wavelengths [7,8] and active cooling of the fiber [9]. In this paper, we reported the in-house fabricated Bi fibers co-doped with phosphorus in terms of absorption, emission, lifetime decay and optical gain to evaluate the efficiency of the obtained fiber. The optical analysis of two pumping wavelengths of 808 nm and 1240 nm are investigated, showing that the phosphorus dopant has stronger influence on the fiber optical performance compared with the influence of silica. From this work, it is noted that the advantage of the fabrication process under study is that the sintering temperature and fiber pulling speed has to be increased in order to reduce the UL. A forward single-pass Bismuth-doped optical amplifier (BDFA) operating within the O-band region was exhibited. Under the 1240 nm pumping scheme, 14.8 dB gain was acquired at 1340 nm signal wavelength. It is cost efficient to pump BDF-based optical amplifiers using feasible and commercially viable diodes such as those at 1240 nm.

2. Materials and Methods

2.1. Bismuth Doped Fiber Fabrication

The Bi fiber was fabricated in-house using the MCVD with in-situ solution doping technique highlighted in [10]. The Bi doped concentration was maintained below 0.02 wt.% in order to avoid clustering. The refractive index profile (RIP) of the fiber preform was measured by a preform analyzer, PK 104 (Photon Kinetics, Beaverton, OR). The core and preform diameters along the preform length were observed to be uniform as depicted in Figure 1a. However, the longitudinal refractive index difference (Δn) showed some variation with an average Δn value of 0.005 (%RSD 14%). The increase of Δn might be due to non-uniformity of the phosphorus doping during the deposition of the core. The preform was drawn into a fiber using a standard fiber drawing tower. The measured core and cladding diameters of the fiber are 7.75 µm and 125 µm, respectively, as shown in Figure 1b. The numerical aperture (NA) of the fiber is measured to be around 0.12.



(**a**) (**b**)

Figure 1. Preform RIP and mirco-scopic image of fiber. (**a**) Refractive index profile of BDF preform (**b**) SEM cross-sectional image of the fiber.

2.2. Bi-Doped Fiber Optical Characterisations

The absorption spectrum from 600–1700 nm was measured by the cut-back method using NKT Supercontinuum white light source (WLS) and an optical spectrum analyzer (OSA) Yokogawa AQ6370D [11]. Figure 2 shows absorption bands peaking at 785 nm and 1400 nm, revealing the association of Bi active centers with silica [5]. The absorption values measured by the OSA at 808 nm and 1240 nm wavelengths are 22.17 dB/m and 3.06 dB/m, respectively. The background loss of the fabricated BDF at 1600 nm, where there is no known influence of dopant, is 0.808 dB/m. A small signal absorption consists of two parts, saturable absorption and unsaturable absorption (UL) [12]. A study in [13] showed that UL increases at shorter wavelength for all types of Bi fiber including Bi-phosphosilicate. As shown in Figure 3, the amplified spontaneous emission (ASE) of the Bi-phosphosilicate is higher compared under Innolume 1240 nmm laser diode (LD) compared with Lumics 808 nm LD. These might be the attributes from the UL at 808 nm wavelength.

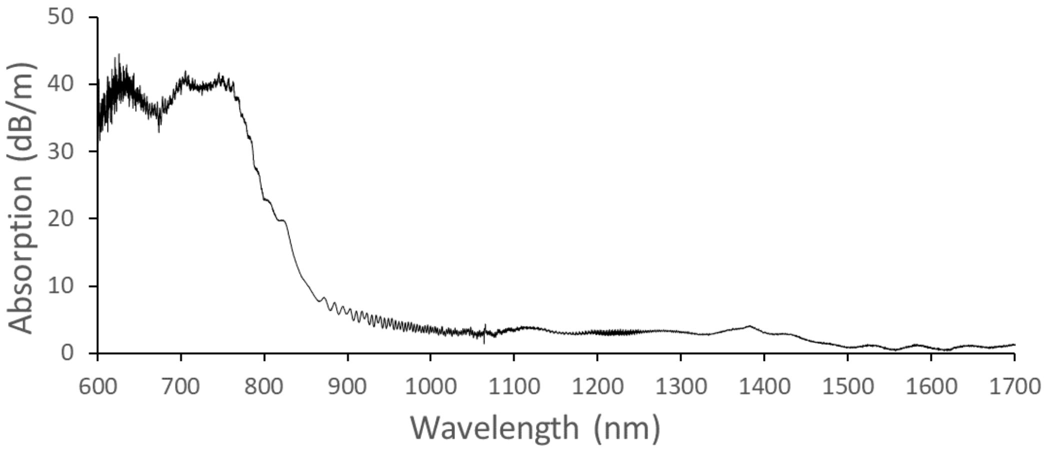


Figure 2. Absorption spectrum of the fabricated BDF.

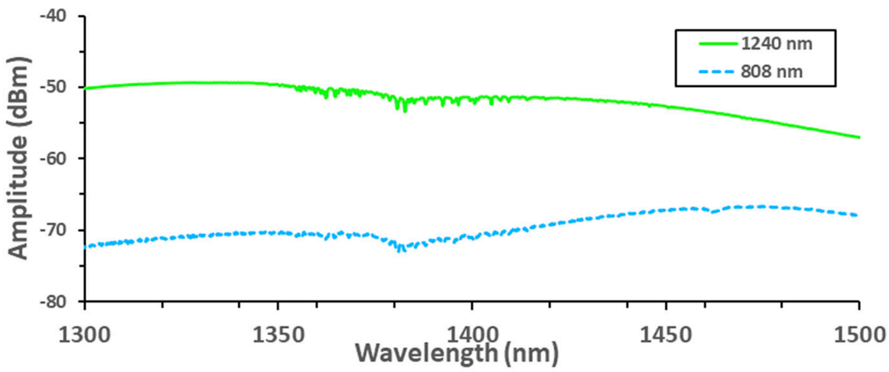


Figure 3. Measured amplified spontaneous emission (ASE) spectra of BDF with phosphorus for 808 nm and 1240 nm pumping wavelengths.

The emission for both pump wavelength falls between the 1300 nm to 1400 nm region. The Bismuth active centers, which bonded with phosphorus in the core, are responsible for this emission region at 1300 nm [5,6]. While the Bi active centers associated with silica is responsible for the emission at 1400 nm region [5]. The emission spectrum is observed to be higher for the 1240 nm pumping wavelength compared with the 808nm pumping scheme even though the absorption is lower than 808 nm wavelength. This shows that the influence of Bi active centers with phosphorus is stronger compared with Bi active centers with silica. The 1240 nm wavelength induces radiative decay rate, an attribute from the population inversion event. However, the population inversion saturates even if a higher pump power is supplied, as there are no more Bi ions available for excitation [3]. This is due to the length limitation of the fiber under test which is only 31 m.

Figure 4 shows the lifetime decay measurement setup. The fluorescence lifetime was evaluated by detecting the fluorescence directly from the optical core through the longitudinal-direction detection setup [14]. The advantage of this method is that even low fluorescence signals can be detected especially in the case of low concentrations doping. To avoid unwanted stimulated emission, the fiber under test (FUT) was kept as short as possible and a minimal pump power of less than 5 mW was used. An index matching gel was used at the tip end of the FUT to ensure that there are no parasitic reflections. An external modulator was used to pulse the signal generated by the pump. The decay lifetime, τ, is the time for the intensity at 1/e from 1 the maximum normalized value of the decay curve [14].

The detector response time is 25 ns which is sufficiently fast to measure the lifetime decay accurately. The response time of the detector must be less than 1/10 of the measured lifetime [14].

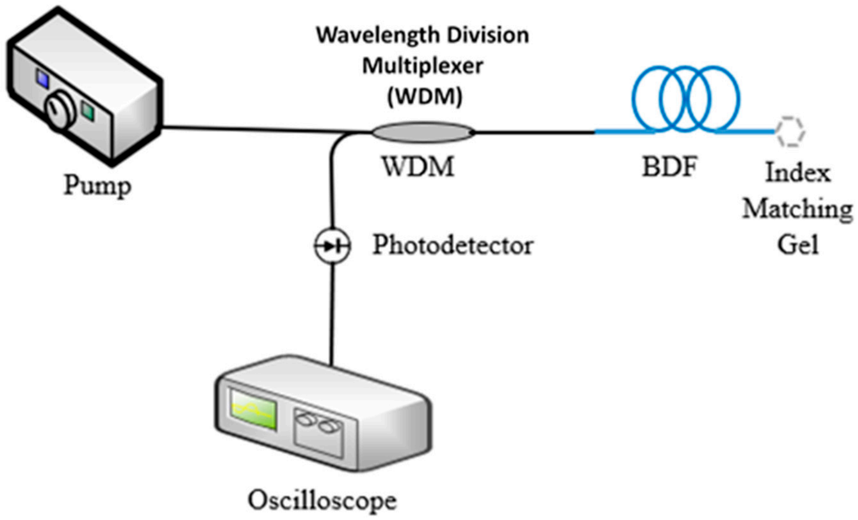


Figure 4. Fluorescence lifetime measurement setup.

The lifetime measurements for both 808 nm and 1240 nm wavelengths are shown in Figure 5. For both 808 nm and 1240 nm wavelengths, the measured lifetime is between 800–850 µs within the 1300 nm to 1400 nm emission region. Even though the lifetime decay for the 808 nm pumping scheme is 50 µs longer than 1240 nm, the ASE level is higher for the latter pumping scheme as shown in Figure 3. As discussed above, the higher ASE for the 1240 nm wavelength can be ascribed to more Bi ions excitations, creating more occurrence of population inversion. Nevertheless, the measured lifetime is the fluorescent decay of an ion regardless of the number of excited ions. The measured lifetime (800–850 µs) corresponds well with previously reported lifetime values for Bi-phosphosilicate fibers [1,15,16].

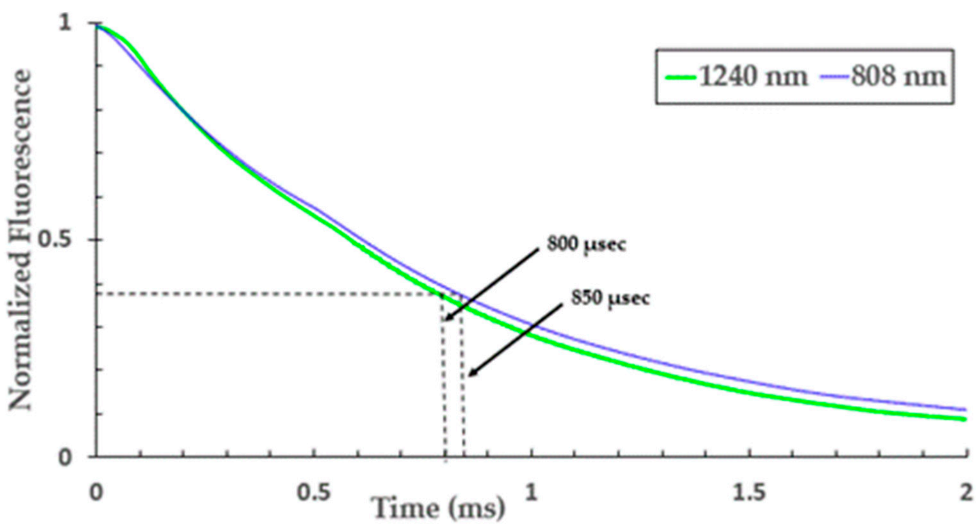


Figure 5. Measured fluorescence lifetime decay.

3. Results and Discussion

Bismuth-Doped Fiber Amplifier (BDFA)

In addition to luminescence characterizations, the optical gain for amplification performance of the Bi fiber was measured by comparing the signal power with and without the presence of the excitation source [17,18]. Figure 6 presents the experimental setup for gain measurement in a single-pass forward pumping configuration. The fiber length used in the setup was 31 m and the cut-off wavelength of the fiber was around 1251 nm. The LD and ANDO AQ4321D tunable laser source (TLS) input signals were launched through a wavelength division multiplexer (WDM) coupler. An attenuator was deployed to dampen the signal input power to −30 dBm.

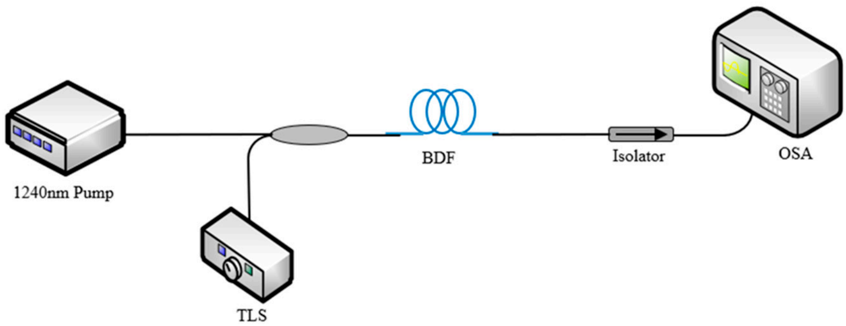


Figure 6. Gain measurement setup for bismuth-doped fiber in a single-pass configuration.

The ASE spectra of the Bi-doped fiber pumped by the 1240 nm LD at different powers are presented in Figure 7. The full ASE spectrum from 600–1700 nm is depicted in the inset of Figure 7. The ASE spectra indicate a saturation at 300 mW pump power. Increasing the pumping power higher than 300 mW is no longer efficient, as the population inversion of the ions is fully achieved. As can be observed from Figure 7, there is a drop in power in the 1380 nm region which can be correlated with the hydroxyl-OH concentration in the fiber [1,5,6]. The interaction between OH groups and Bismuth ions may cause gain reduction in the 1380 nm region [18]. The interaction between Bi ions and impurities in this case is that OH molecules can result in UL phenomenon. The UL in fiber leads to an increase in the pump lasing threshold, thus causing poor efficiency [7,8,13,18]. It is reflected in [19] that the UL in BDF is influenced by the fabrication conditions, namely the soot sintering temperature and the fiber drawing speed. In this work, the Bismuth-phosphorus doped silica soot was sintered by two consecutive passes of the oxyhydrogen burner at temperatures of 1650 °C and 1800 °C. The fibers were drawn with feed and a drawing speed of 0.10 mm/m and 1.5 m/m at 2070 °C. In [19], the optimization of the fabrication process deployed a higher sintering temperature and speed. The fabrication process can also be optimized to reduce the OH concentration, for example by utilizing vapor phase doping of Bismuth.

The measured signal gain for the BDFA at different signal wavelengths (1320–1490 nm) is shown in Figure 8. The input signal power is set at −30 dBm and the pump power varies starting from 100 mW to 300 mW. As is illustrated in the figure, a maximum gain of 14.8 dB is obtained at 1340 nm wavelength when the pump is at 300 mW. For all three pump power variations, the gain decreases towards the tail end of the ASE spectrum. This shows that the influence of Bi active centers with silica is weaker compared with Bi active centers with phosphorus. The gain of the BDFA is dependent upon the energy stored inside the amplifying medium, which is observed as the ASE. The gain variation with increasing pump power at the signal wavelength 1340 nm is shown in Figure 9. The analysis of the gain characteristics at various pump power levels is critical to understand the dynamic behavior of the BDFA. A maximum gain is obtained with a pump power of 300 mW. The gain is observed to increase sharply from 50–200 mW with a 14% increment. It then starts to saturate with an increment of only ~3% from 200–300 mW. It should be noted that a longer BDF length allows a higher gain as more Bi ions can be supplied to enhance the gain.

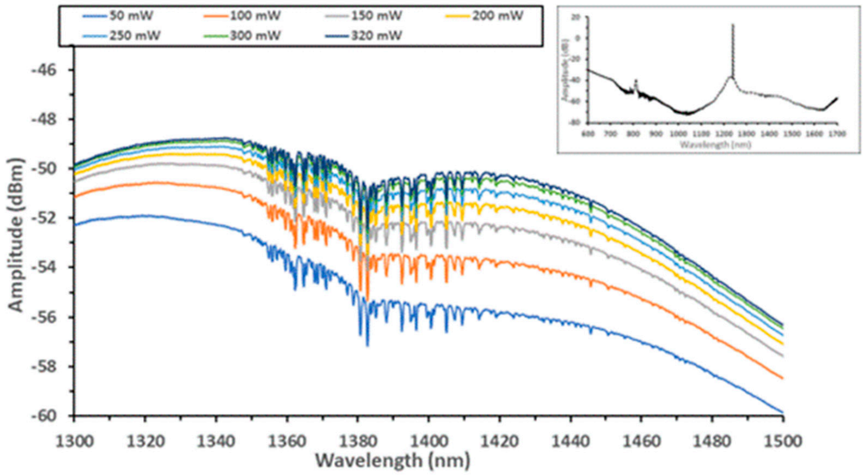


Figure 7. Measured ASE spectra at different 1240 nm pump power levels. (Inset) Measured ASE from 600–1700 nm at 50 mW pump power.

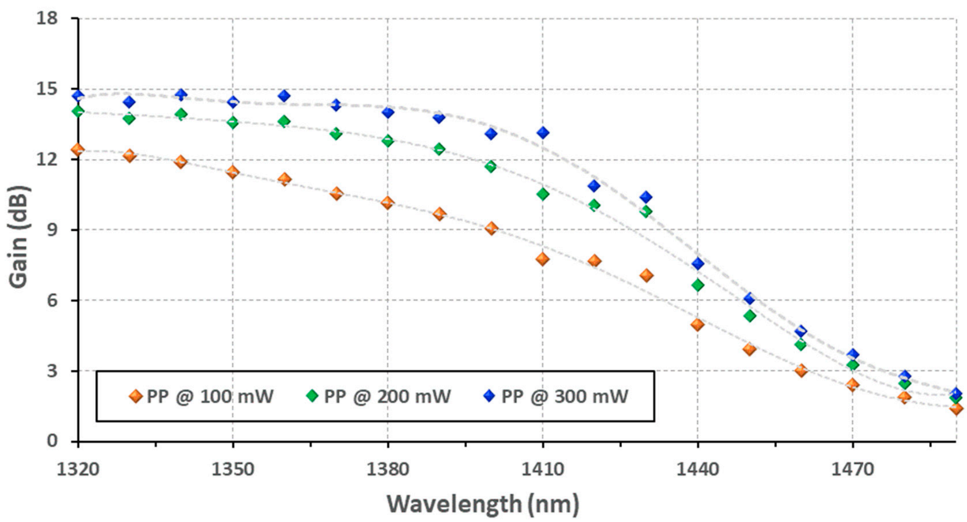


Figure 8. Signal gain for the BDFA at different signal wavelengths at different pump powers.

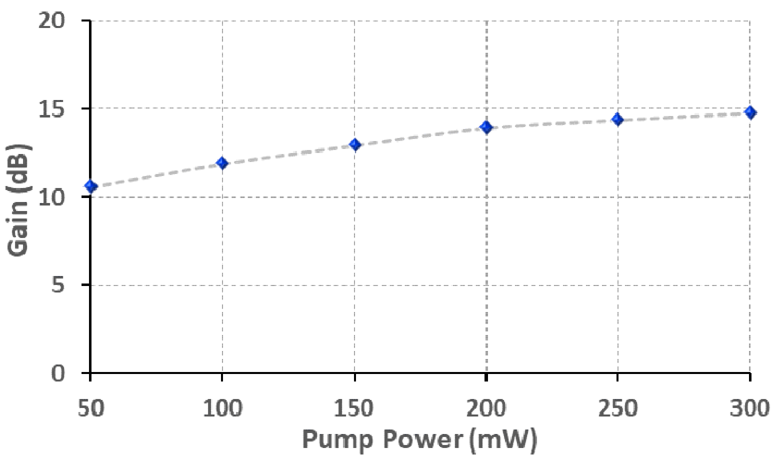


Figure 9. Gain versus pump power variation for 1340 nm signal input.

4. Conclusions

This paper has presented the fabrication and characterization of a Bismuth-doped phosphosilicate fiber. The optical fiber preform is fabricated using the MCVD with an in-situ solution doping method. The fabricated BDF has a core diameter of 7.75 µm, an NA of 0.12 and a cutoff wavelength of 1251 nm. An ASE spectrum with a 3 dB bandwidth from 1320–1500 nm has been obtained with pump wavelengths of 808 nm and 1240 nm. It has been pointed out that the gain profile of the BDFA strongly depends on the pump wavelength and the fiber core composition. A maximum gain of 14.8 dB has been achieved with a 1340 nm input signal and 1240 nm pump wavelength. Increasing the BDF length and optimizing the fabrication process to reduce the UL effect may improve the gain and is the objective of our future research on BDFA. Bi-doped phosphosilicate has been shown to be highly sensitive to fabrication parameters, and comprehensive considerations in the fabrication process are important to ensure the quantum efficiency of the fiber.

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