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An Overview of Free Space Optics with Quantum Cascade Lasers

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***Abstract*—The article presents an overview of the work on quantum cascade lasers application in free space optical systems (Free Space Optics - FSO). There are discussed the main issues of the open-space laser communications and their practical construction. Comparative analyses of each FSO technology were performed. Brief description of quantum cascade (QC) lasers and some developments related to the use of these lasers in optical data link are also presented. In summary, the constructed models of FSO links with QC lasers are characterized.**

***Keywords*—quantum cascade laser, free-space optics, laser communications**

I. Introduction

FSO data link is a wireless communication technology, in which the data is transferred by optical radiation transmission in free space. This technology can be an alternative or complement tool to other non-wire communication systems. Compared with radio systems, it provides an increase in the level of data security and communication accessibility due to the much lower beam divergence and immunity to electromagnetic interference. The choice of the radiation wavelength depends largely on the transmission properties of the atmosphere and radiation safety. Some transmission windows used in FSO systems correspond to the spectral ranges around three wavelengths: 800 nm, 1.5 µm and 10 µm.

But commercially available FSO links operate mainly in the near-infrared (NIR) and mid-infrared (MIR) spectral ranges (e.g. from Terabeam, AirFiber, LightPointe) [1]. Using these instruments, data transmission rates from 1.5 Mb/s to 1.5 Gb/s over distances of up to 6 km can be obtained. Practically, the transmission rate strictly depends on the weather conditions. The increase in data bit rate is achieved at lower distances (for moderate climate, the range is usually less than 1 km).

Analysing the FSO operation idea, it can be seen that its construction has been optimized taking into account e.g. the power of radiation source (single or multiple sources), the parameters of optical elements (aperture, optical transmission, and divergence), detectivity of photoreceiver (single detector or detector matrices), signal bandwidth, coding, and modulation. However, the main limitation on FSO system parameters is unpredictable weather conditions. Figure 1 presents the optical transmission of the atmosphere for two different visibilities 200 m (a) and 50 m (b). It can be seen, that for bad weather, better transmission for laser beam with longer wavelength is observed. But for a long time, the longwave (LWIR) infrared spectral range was considered as a perspective technology. The main limitation was the lack of suitable radiation sources (in comparison CO_2 lasers were complex or offer low-speed modulation) and a high-sensitive and ultra-fast detectors. However, the development of QC lasers and MCT detectors operating in the LWIR range initiated research on a construction of a new generation of FSO links [2].

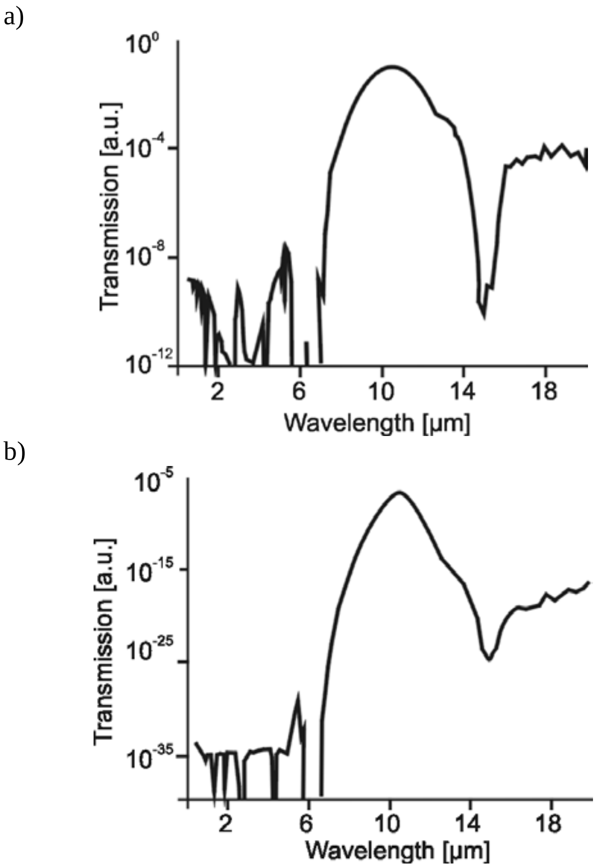

Fig. 1. Transmission of the atmosphere at the distance of 1 km and for the visibilities of 200 m (a) and 50 m (b) [3]

II. Quantum Cascade Lasers

Quantum cascade lasers are an important step in the development of laser radiation sources. They are a new class of unipolar semiconductor lasers, whose operation is based on inter-band transitions. During these transitions, the optical

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radiation in the range of near to far infrared (from 3 microns to 100 microns) is emitted.

When selecting the QC laser to FSO system the main issues should be the spectral range and the radiation power. Currently, laser structures with configuration of Fabry-Perot (FP), distributed feedback (DFB), and distributed Bragg reflector (DBR) are available on the market. These lasers can operate in continuous or pulse mode. For FP laser, much higher value of radiation power and multi-mode operation is obtained [4]. In pulsed operation (with pulse length up to 300 ns), the peak power reaches even a few watts. But increase in pulse duration can cause a significant growth in the structure temperature, the pulse power decreasing and even the laser structure damage. Figure 2 shows the influence of pulse duty cycle on both average light power and peak power for two different values of pulse duration. For DFB lasers, emitted radiation is characterized by the power level of several to several hundreds of mW and by single-mode structure.

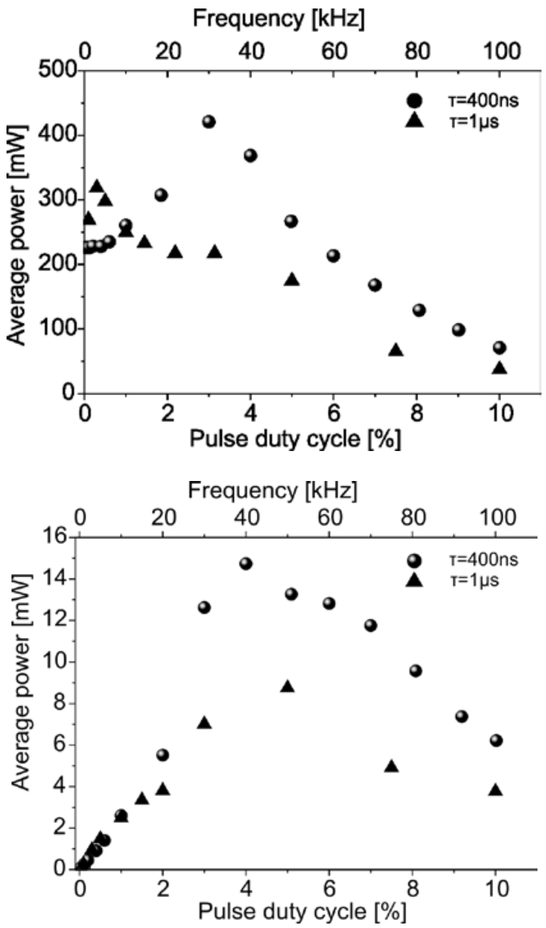

Fig. 2. Influence of pulse time duration on radiation peak power (a) and average power (b) [5]

High capability of quantum cascade lasers in communications systems is also determined by high-frequency modulation of radiation pulses. The modulation limit is defined by the lifetime of carriers in the inversion state. In quantum cascade lasers, this lifetime can be matched by properly designed active area. Typically, carrier life-time varies from a few *ps* to a few hundreds of *fs*. The time value depends on e.g. the distribution of the wave functions and the difference between the output energy level and the final one. Thus, dynamics of population inversion in the QC laser is significantly higher compared to other semiconductor laser (up to three orders of magnitude or more.) That is why, the short carrier life-time and negligibly small chirping effect are the main advantages of QC lasers for use as an ultra-fast pulsed radiation source.

Nowadays, there are some works on FSO systems, which use the above features of these lasers. However, QC laser's driving require high level of both current and voltage signals. That is why, it is very important to apply a special construction of power supply and temperature control. In practice, a significant reduction in modulation bandwidth is also observed. This effect is caused by technology of driving signals and the laser structure link. In the ideal case, the connection ought to take into consideration the impedance matching and the impact of reactive-electrical elements. However, each QC laser is unique and is characterized by different electrical parameters. Therefore, an individual compensation procedure for signal bandwidth should be prepared.

The described aspects concern so-called direct amplitude modulation of radiation by changing the control current. But continuous work on an ultra-high speed modulation is still performing. The final results follow directly from the theoretical limit of quantum cascade lasers operation (carrier life-time). Currently, there is a few works on optically stimulated generation of ultra-short pulses [6]. In addition, the generation of the laser pulses using microwave techniques has been also presented. For this purpose, special constructions of QC laser structures with microstrip lines have been tested – Fig. 3. In such systems, the modulation bandwidth of 13.5 GHz was obtained.

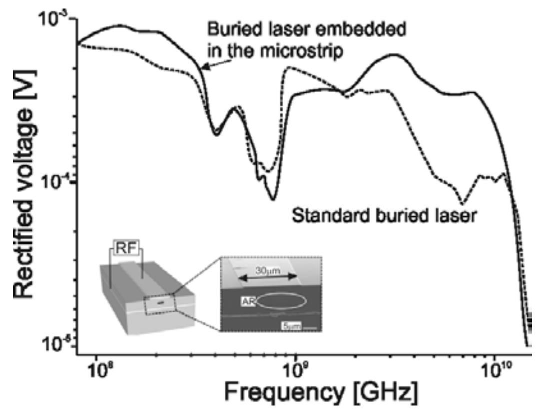

Fig. 3. Measured rectified voltage at 77 K for a laser in standard buried waveguide and a laser embedded in the microstrip as function of the modulation frequency. Inset: schematic and SEM image of the laser embedded in the microstrip line [7].

Currently there are also performed works on the methods of spectrum modulation. The first attempts focused on quantum cascade lasers operating in CW mode. These studies have shown that the QC lasers can work as spectral modulators in FSO systems without fundamental modification of their structures [8].

III. Overview Of FSO Systems

The first study on QC laser application in optical communications appeared in 2001-2002. There were presented a few FSO laboratory systems that use high-power lasers with liquid nitrogen cooling. For example, Capasso et al. describes a setup in which AlInAs-GaInAs laser was used [9]. The laser wavelength was 8.1 µm. It operated in CW mode (at the temperature of 77 K) with both efficiency slope of 0.51 W/A and the driving current of (150 - 300) mA. In the photoreceiver, QWIP detector was used. At the distance of 1 m, transmission speed of 2.5 Gb/s was obtained. The applied laser provided modulation with frequency of 7 GHz, which corresponds to the standard broadband connection. But the modulation response was RC-limited with capacitance across the layers and the laser differential resistance (operating above threshold). For the optimal set of system parameters, BER value of 10^{-12} was measured. During that study, the outdoor test of the modified communication system was also performed. The data link distance was 100 m. In the receiver block, an optical telescope and a fast cryogenically cooled MCT detector were used. The laser was driven using complex signal (corresponds to digital data and biasing one). The bandwidth of this signal was in the range of (0.75 - 1.45) GHz. For the biasing current of 100 mA and the temperature of 20 K, the data link was working for 5 hours with the pulse power of 7.5 mW. To transmit data, QPSK code enabled the transmission of nearly 800 television channels and 100 radio channels was applied.

Further development of the QC laser technology made it possible to design FSO system without cryogenic cooling. In the transmitter, laser emitting at the wavelength around 9.3 microns was mounted. The optical radiation was collimated using Ge lens (f/0.8) with a diameter of 37.5 mm. The laser operated at the temperature of 150 K with the max. duty cycle of 50%. For laser driving, a special bias-T circuit was designed. In the circuit, two signals were added. The first one was a constant bias current of 2 A (72% of the threshold current), while the second one correspond to data pulses with bandwidth of 350 MHz. In the FSO receiver, a reflecting telescope with a diameter of 16 cm and high-speed MCT detection module working at the room temperature (with the detectivity of $2.2\ 10^{7}$ cm √Hz/W) were placed. For the temperature of 258 K and the pulse duty cycle of 50%, the laser threshold current was 3.2 A. It provided to obtain the average optical power of 14 mW. To transfer data, the RS232 interface with bit rate of 115 kb/s was prepared.

In addition to the described laboratory FSO links, there were also developed a few technological demonstrators and their commercial versions. Such device was designed e.g. at the Center for Quantum Devices, USA. In the transmitter, QC laser pulses with the wavelength of 4.8 µm and the power of 200 mW were applied. The laser operated at the room temperature with the bias current of 0.75 A and the supply voltage of 12 V. The cooling system was built with a thermoelectric cooler. Optical beam was collimated using ZnSe spherical lens with diameter of 3 mm. The FSO system was battery powered for 4 hrs. As an interface, RS232 communication standard was applied. In the receiver, the superlattice InAs/GaSb detector with the cut-off wavelength of 5 µm was placed (the detectivity of $1\ 10^{9}$ cm√Hz/W). The laser module provided to work with the max. duty cycle of 45% and the min. pulse duration of 200 ns (for a bit rate of 10 kHz). Figure 4 shows a view of the FSO transceiver links.

In a few science papers it was mentioned that two commercial FSO links with QC lasers were also constructed.

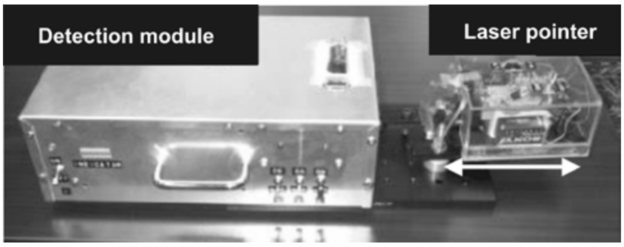

Fig. 4. Photo of the FSO transceiver [10]

The links were manufactured by the Maxion Corporation and the Fraunhofer Institute for Physical Measurement Techniques IPM. The first one was developed in 2003 but there is no more data. While the system from the IPM is currently offered in the form of a portable system (Fig. 5) [11]. The catalogue data of this system contains only information on the spectral range of laser and detector operation (2.5 µm-10 µm). The measured signal bandwidth is 155 Mb/s. The presented data range is 1.5 km with modulation bandwidth exceeding 1 GHz.

Fig. 5. Photography of the FSO system offered by IPM, Germany

IV. Results Of Own Work

At the Institute of Optoelectronics MUT, some works on optical communication system using cascade lasers have been also performed.

An initial step in FSO system construction operating at the wavelength of 10 microns was taken in 2006 (1st Generation). In the transmitter, QC laser system prepared by Cascade Technologies Company was used. It enabled to emit optical pulses with the max. frequency of 100 kHz, the duty cycle of 1% and peak power of 100 mW. The receiver consisted of reflective optics produced by Janes Technology (USA), MCT photodiode with low-noise transimpedance preamp constructed by Vigo System SA (Poland). During hazy weather conditions (visibility of 500 m), the data range of about 1000 m with BER value of 10^{-12} was obtained. Figure 6 shows photographs of the designed FSO transmitter (a) and receiver (b). The main limitation of this system was the restricted range of laser pulses parameters (repetition rate and duty cycle).

a)

b)

Fig. 6. Photographs of the designed FSO transmitter (a) and receiver (b)

Exceeding that range, the laser structure may be damaged. But for pulse time duration below 20 ns, the laser did also not generate radiation. During the system tests, there were observed changes of the shape for different pulse time duration. Square shape of optical pulses was obtained only for the driving pulses of 100-180 ns. But increasing time value, the extinction of the laser pulse is noticed– Fig. 7. This phenomenon dictates the need for RZ coding with a low duty cycle.

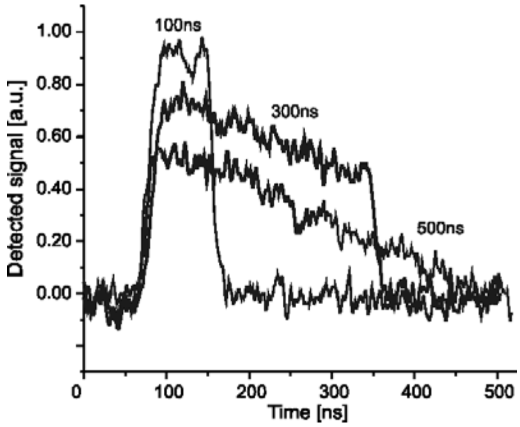

Fig. 7. Laser pulses for different values of pulse time duration

An important element of the FSO link was the communication bridge. The main task of this bridge was to encode both the digital signal from data network on the form acceptable by the laser driver and photodetector output signal on digital one. Because the laser pulses have max. repetition rate close to value of 100 kHz, as the communication standard RS-232 interface was used. In Table I some performance of this data link are listed.

TABLE I
THE MAIN PARAMETERS OF THE FSO SYSTEM (1ST GENERATION)

Parameter	Value
wavelength	10 µm
peak power	100 mW
detectivity	3.2 10^9 cm $Hz^{1/2}$/W
beam divergence	1.5 mrad
data range (BER = 10^{-12})	1.5 km (Vis = 2km)

The continuous development of semiconductor technology enabled the design QC lasers characterized by a higher power, frequency and duty cycle of optical pulses. For that reason, a new model of the FSO link with a QC laser system from Alpes Lasers SA company was constructed (2nd Generation). Operation characteristics (a) and spectrum (b) of the laser are shown in Fig. 8.

The main issue of preliminary studies was to determine the influence of the QC laser operating point on the shape of the optical pulses. In Figure 9 there are presented waveforms recorded on the photodetector output for different levels of the laser driving signal.

It can be seen that at the low values of the biasing voltage, power peaks occur. This phenomenon can be caused by the properties of the laser driver, the technology of signal-laser structure link, and dynamic shift of the operating point caused by temperature change of the laser structure.

a)

b)

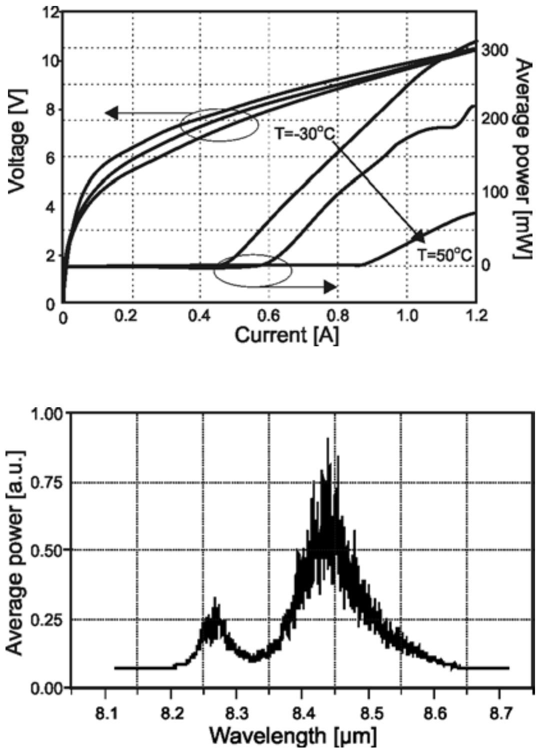

Fig. 8. Characteristics of QC laser model #sbcw2968: light-current-voltage (a) and spectrum (b) [12]

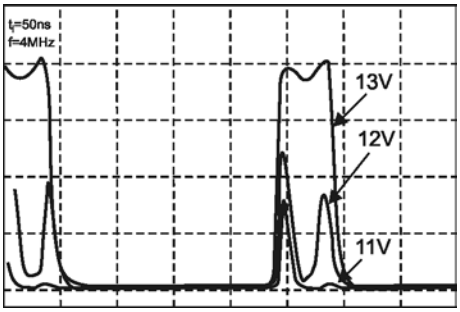

Fig. 9. Laser pulses for different amplitude of biasing voltage

Figure 10 shows the shape of the laser pulse for various operational temperatures. The decrease in the temperature causes a considerable increase in power pulses, however, it requires a high-performance cooling system. Additionally, for large values of pulse duty cycle, it is necessary to use water cooling.

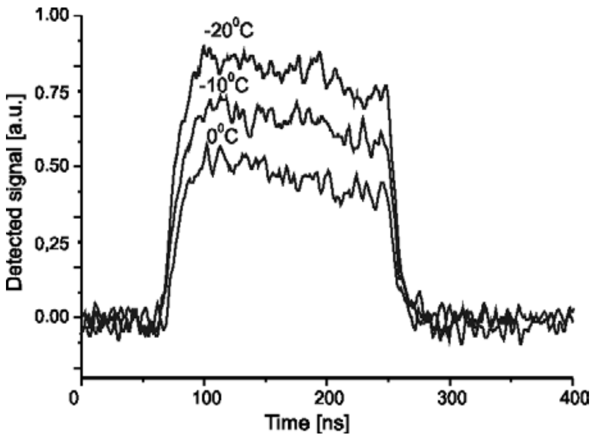

Fig. 10. Laser pulses for different values of laser temperature

The FSO transmitter consists of an optics, laser head, power supply and control unit, cooling block and control system for beam position (divergence of 2.5 mrad) – Fig. 11a. In the FSO receiver Ge lens, detection module with MCT detector (detectivity of 3.8 10^9cm √Hz/W), signal processing circuit, electronic comparator, and an interface block are mounted– Fig. 11b.

The FSO link parameters were studied using a pseudo-random generator Picosecond 12 000. In Figure 12 examples of pulses registered for RZ and NRZ coding are shown. For both coding modes, data transmission with the frequency of 1 MHz and the max. pulse duty cycle of 50% is provided. But there is noticeable distortion of pulse shape for NRZ coding signals. These effects may result from the previously described factors affecting the laser operation point.

a)

b)

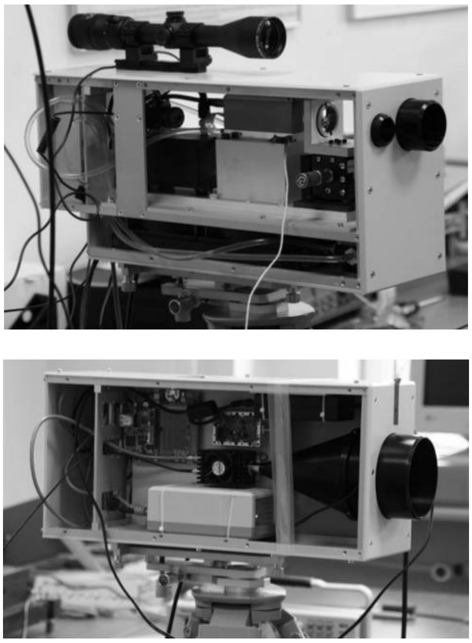

Fig. 11. Photo of the FSO transmitter (a) and the FSO receiver (b) (2nd generation) [11]

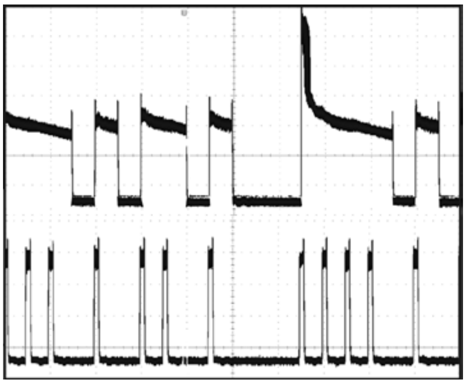

Fig. 12. Laser pulses for different formats of pulse coding (RZ and NRZ)

For data transmission, a special network bridge was applied. It works with data buffering. Data are received in the frames via Ethernet analysing their contents and correctness. Using such setup, the data rate of 2 Mb/s with the theoretical range of 2.5 kilometres was obtained (for BER = 10^{-9}).

V. SUMMARY

The paper presents an analysis of quantum cascade lasers properties taking into account their application in free-space communication systems. Some significant advantages of these lasers, e.g. LWIR spectrum with low atmosphere attenuation, eye-safety operation, and compact construction were pointed. The design of QC laser structure (ultra-short life-time of carriers) makes it possible to obtain very fast modulation of the radiation power. However, this requires the use of high-efficient and high-speed control circuits. In practice, such demands can be a significant limiting factor. A new direction of research is the optical/microwave modulation of QC laser radiation. There are also presented some constructions of FSO systems with quantum cascade lasers, which have been developed since 2000. Noticeable progress in the development of these systems was mainly directed to improve working conditions (e.g. temperature operation) and to increase the radiation power and modulation bandwidth. Nowadays, the modulation rate has not exceeded the value of 1 GHz. There were also described the results of performed research at the Institute of Optoelectronics, MUT. The main achievement was to construct FSO link (2nd Generation) with QC laser produced by Alpes Lasers SA Company. The further work is to analyse the FSO applicability of quantum cascade lasers produced at the Institute of Electron Technology, Warsaw, Poland.

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