Contributed paper

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Impressing technology of optical Bragg's gratings on planar optical sol-gel waveguides

T. PUSTELNY*, I. ZIELONKA, C. TYSZKIEWICZ, P. KARASIŃSKI, and B. PUSTELNY

Institute of Physics, Silesian University of Technology, 2 Krzywoustego Str., 44-100 Gliwice, Poland

The aim of the presented investigations was to develop a technique of producing Bragg's grating couplers on planar waveguides. Waveguides are obtained by means of the sol-gel technology. The introduction of a light beam into the structure of the waveguide is in the case of planar or strip optical systems always an essential technical problem, requiring simple and reproducible solutions without extending excessively the waveguide structure. The paper presents a technology of producing grating couplers by impressing the pattern of the network while forming the planar waveguide structure applying the sol-gel method. Some remarks concerning the sol-gel technology are also presented. The results of investigations on grating couplers obtained in such a way have been discussed, too.

Attention has been drawn to the possibility of using such structures in optoelectronic sensors, particularly gas sensors, including sensors of water vapour as well as toxic gases.

Keywords: Bragg's grating couplers, integrated optics, optical waveguide technology.

1. Sol-gel method of optical slab waveguide production

In Ref. 1, the most popular methods of the production of the planar optical waveguide structure have been presented. One of the methods of waveguides producing is also the sol-gel method. This method possesses some essential advantages and was discussed, e.g., in Refs. 2–6. It permits to get waveguide layers in a very wide range of refractive indices n = 1.4–2.2. This method is not technologically complicated and does not require any expensive and special technological equipment.

The sol-gel method is a low-temperature method of synthesizing organic material or synthesizing organic and inorganic materials [2,4,7]. Sol is a colloidal solution, i.e., a system composed of the dispersive phase (liquid) and the dispersed phase (solid). Gel is a macroscopic particle taking up the entire volume of the solution.

The sol-gel method is based on hydrolysis and condensation of the initial components – the precursors in an alcoholic solution. The precursors are those substances which participate in the first stage of the reaction. The precursors used in the sol-gel technology affect the optical properties as well as the porosity and hardness of the obtained dielectric waveguide layers. Of special interest are the optical properties of the obtained layers, particularly the refracting indices.

The sol-gel technology for optoelectronic applications has often made use of multicomponents silicate structures comprising TiO_2-SiO_2. The TiO_2-SiO_2 waveguide layers are obtained by using solutions of tetraethoxysilane (TEOS) and tetramethhoxysilane (TET) as precursors of Si and Ti [2,7].

In this technology, the precursors were dissolved in water and ethyl alcohol (EtOH). The solvents prevent the separation of two liquid phases during the initial hydrolysis and permit to control the silicon and water concentration which affects the kinetics of the gelling process. The rate of the process is affected by the presence of a catalyst which in our case was HCl acid. The gel is the result of polymerization processes. In the presented investigations, the waveguide layer structures consisted of SiO_2-TiO_2. The TEOS solution was in the following proportions: TEOS:EtOH:H_2O:HCl = 1:4:1.5:0.08. This solution was then placed for 60 minutes in an ultrasonic washer at a temperature of 50°C (323 K). In the course of the following stage, the TET-solution was added to the partially hydrolyzed TEOS solution. The TET-solution was prepared in molar proportions: TET:EtOH:H_2O = 1:10:1.5. The molar ratio of the final solution was: TEOS:TET = 1:1. The final solution has been placed in an ultrasonic washer at 50°C and mixed for several hours (1.5, 3, and 4.5 hours). The portions of solutions were denoted as A, B, and C, respectively.

Deposition of wave layers was realized by immersing sodium-calcium glass plates in A, B, and C sol-gel solution using the appropriate lift. The rate of lifting the plate with sol-gel solution decided on the thickness of the waveguide layers and their mechanical as well as optical properties. The rate of lifting was 2–4 cm/s. For 2 cm/s the thickness of the waveguide layers was about 170 nm while at 4 cm/s

*e-mail: tpustelny@polsl.pl

it amounted approximately to 250 nm. The technological problems of sol-gel waveguide production were presented in detail in Refs. 8 and 9.

These layers were then dried for several hours at a temperature of 20°C, after which the layers were kept for 2 hours at the higher temperatures (200°C, 250°C, and 300°C, respectively).

Disadvantages of the sol-gel method are the limited repeatabilities both of the thickness of the produced waveguide layers and their refractive index. Layers produced by the same technology may differ in their thicknesses up to 1–2% and the refractive indices up to $\Delta n = \pm 0.002$. Those waveguides are characterized also by the values of the attenuation coefficient (α = 2–3 dB/cm) higher than those in other technologies (e.g., ion exchange method). For sensor applications, these limitations usually are not important.

2. Methods of light exciting in optical waveguides

The problems concerning introduction and extraction of the light beam in the planar waveguide are of essential importance in the integrated optics.

There are several ways of exciting the light in optical waveguides [10]:
- from the front (through the normal surface),
- by means of the skew-cut edge of the waveguide,
- by means of prismatic couplers,
- by means of grating couplers.

The former two methods are characterized by a poor effective coupling (only of the order of some percentages). The prismatic coupler is generally applied in planar optical systems, although in this case the plane structure of the waveguide layer is three-dimensional, which may result in an additional restriction of its application.

The application of Bragg's gratings as couplers in planar optics was mentioned for the first time by White et al. [11]. The grating coupler is a structure based on the waveguide, the refractive index of which varies periodically along the path of the light propagation. An idea of the configuration of a grating coupler is shown in Fig. 1.

The phase matching condition that must be satisfied in order to couple the incident beam to the guide is

$$k_1 \sin\Theta_i - \beta = m\frac{2\pi}{\Lambda}, \text{ where } m = 0, \pm1, \pm2, \pm3... \quad (1)$$

where k_1 is the wave number of incident light, β is the propagation constant in the waveguide, Λ is the grating period, Θ_i is the angle of incidence, and m is the integer.

Analyses of light propagation in grating couplers have been presented, among others, in Ref. 12. Due to the factor m, a mode can be excited using various values of the angle of incidence Θ_i. In reverse, this means that the guided mode passing along the grating can be partly coupled out to multiple beams, each of them radiating into one of these angles.

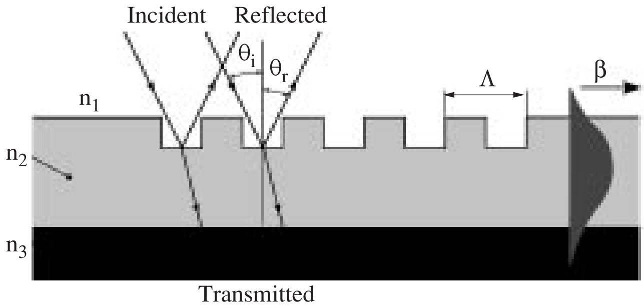

Fig.1. Idea of a light grating coupler

The efficiency of the grating coupler amounts theoretically to 60%. Actually, however, such couplers display a practical efficiency of only 30%, because a large part of the energy of the incident beam is refracted and fades in the glass substrate. A higher efficiency of coupling (up to 70%) can be achieved utilising the asymmetric profile of the coupling grate [13]. The grating coupler is less effective than the prismatic one. Its doubtless advantage is, however, its compatibility with the monolithic conception of integrated optoelectronic systems. The theory and technology of grating couplers have been presented, among others, in Refs. 14–17.

3. Periodical structures – methods of their production

Bragg's planar gratings are produced mainly by means of three techniques of periodical perturbation [15]:
- electron technology methods,
- optical methods,
- mechanical impressing of the grating on the surface of optical waveguides.

From among the electron methods, the focused beams of electrons or ions are utilized to draw the shape of a grating on planar optical waveguides. The advantage of these methods is the possibility of getting structures smaller than 200 nm. Their drawback is that such processes are expensive, requiring special equipment, and long-lasting. Therefore the number of users applying them for sensor applications is rather limited.

Optical methods of producing the pattern of the diffraction grating require photo-sensitive waveguide layers or coatings. Periodical structures are produced in these layers by exposing them to ultraviolet light [18,19]. The grating structures are periodical variations of the refracting index of the layers after their exposition to UV radiation. These methods also require specific (and expensive) devices.

Mechanical impressing of the pattern of the periodical structure is applied for layers susceptible to deformations.

This method may be used to activate periodical disturbances in the layers deposited by means of the sol-gel method and also in polymeric layers [1,14].

The method of mechanical imprinting in the production of periodical structures in a planar waveguide of the type

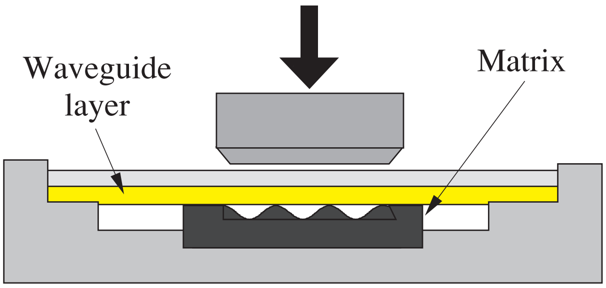

Fig. 2. Idea of the practical realization of the mechanical imprint method.

SiO_2-TiO_2 was applied by Lukosz and Tiefenthaler [20]. The obtained structures were used by the authors as Bragg's grating couplers and mirrors. Basing on this method, as Szandro suggested in Ref. 21, periodical structures of the type: SiO_2, TiO_2, Ta_2O_5, SiO_2-TiO_2 may be obtained.

Figure 2 presents the idea of activating a periodical disturbance on a planar sol-gel waveguide by impressing the pattern of the grating. The matrices, which are the patterns of the imprinted gratings, were produced during the process of electron etching on silicon substrates and were performed at the Institute of Electron Technology in Warsaw. The length of one disturbance in the matrix amounted to about 4000 nm. The size of the matrix is a square of 4×4 mm.

In order to obtain periodical structures, an adequate mechanical system has been constructed permitting realization of the imprint method. This system was presented in Ref. 14.

4. Periodical waveguide structures

The production of Bragg's grating structures with mechanical imprinting of the grating pattern become possible after the technology of producing single-mode planar waveguides by means of the sol-gel method had been mastered.

Numerous grating couplers have been made on various substrates with a deposited waveguide layer at various rates of extracting the substrate glass plates from the gel solution. These tests have made it possible to determine the approximate time interval after the plate had been taken out of the sol-gel solution, in which the waveguide layer is elastic enough to permit the periodical structure to be imprinted.

Investigations have proved that if the layer is too hard or too soft, imprinting of a grating is impossible because the obtained structures are strongly deformed. Basing on carried out tests, it can be assessed that in the presented system the periodical structure can be imprinted in the course of about 3–4 minutes after the waveguide layer has been deposited on the glass substrate by means of its rating from the sol-gel solution. It has been found that after about 4 minutes the layer has become too hard for getting a periodical structure with satisfying optical properties.

In our situation, the periodical structure was imprinted up to 3 minutes after the deposition of the waveguide layer. The quality of the obtained periodical structure depends on the forces with which the matrix is pressed to the layer. If the exerted force is too high (per surface unit) or too small, the layers adhere to the matrix and their fragments are torn off from the sol-gel solution, which leads to a permanent deformation of the periodical structure. In our first processes, the applied pressure amounted up to about 0.1 MPa. The sol-gel waveguides with the obtained grating structures were then kept for two hours at temperatures of 200°C, 250°C, 300°C, and even 400°C to get hard.

The obtained periodical structures were subjected to investigations in an atomic force microscope in order to check the quality of the obtained gratings and determine the accurate value of the constant Λ. Measurements have shown that Λ = 1000 ±1 nm (fully conforming to the value determined by the producer of the grating matrix).

5. Investigations of grating couplers

The obtained grating couplers were tested in the set-up presented in Fig. 3.

In order to position the periodical waveguide structure versus the direction of the laser beam precisely, a goniometric table was used. The tested structure was illuminated by a laser diode (DL) with a wavelength of 677 nm and modulated by a signal from a generator with a frequency of 1000 Hz. The applied goniometric table permitted the introduction of a light beam with a known polarization into the waveguide. The rotation of the goniometric table forced the step motor, controlled by a computer. The accuracy of rotation of the goniometric table was a 2" angle. The optical modes which propagated in the waveguide structure were transmitted to the photodiode by the optical fiber. The testing of the waveguide consisted in measurements of the light propagated in it as a function of the angles of its activation. In the detection system a homodyne nanovoltmeter was used, from which the output signal was directed towards the measurement card in the computer.

First investigations have shown that the quality of the obtained waveguide structure with a grating coupler was rather dissatisfactory. Such a conclusion was later confir-

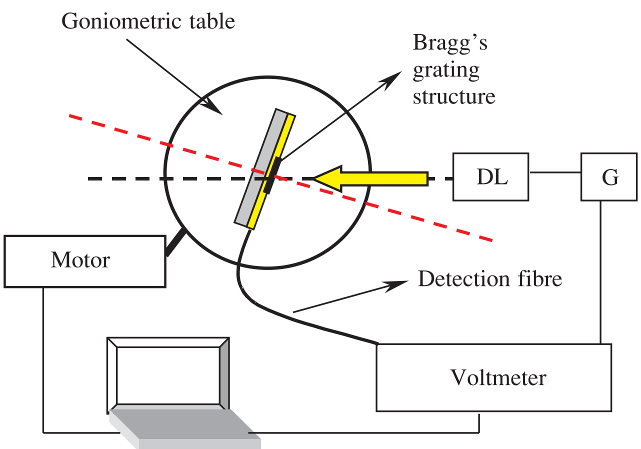

Fig. 3. Diagram of the set-up for the testing of grating couplers (DL – laser diode, G – generator).

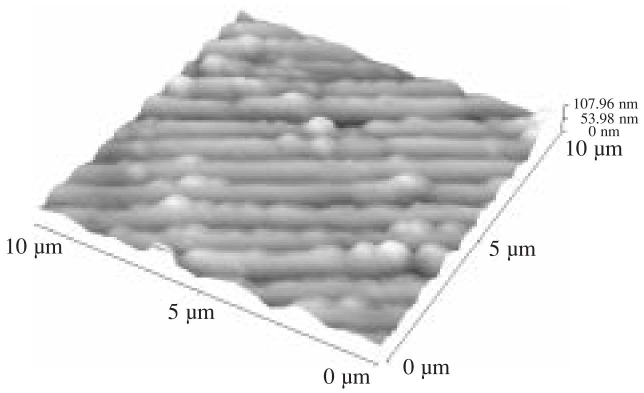

Fig. 4. Example of the grating structure obtained in first technological processes (image by an atomic force microscope).

med by investigations carried out in a microscope of atomic forces (AFM). The image of the structure obtained by AFM is presented in Fig. 4.

Figure 5 presents the mode characteristic of this structure. Investigation (realized in the set-up presented in Fig. 2) shown that in the waveguide structure some modes are propagated in that group of refractive modes, too. The total efficiency of the coupling between propagating and exciting energy was estimated to be of the order of several percents.

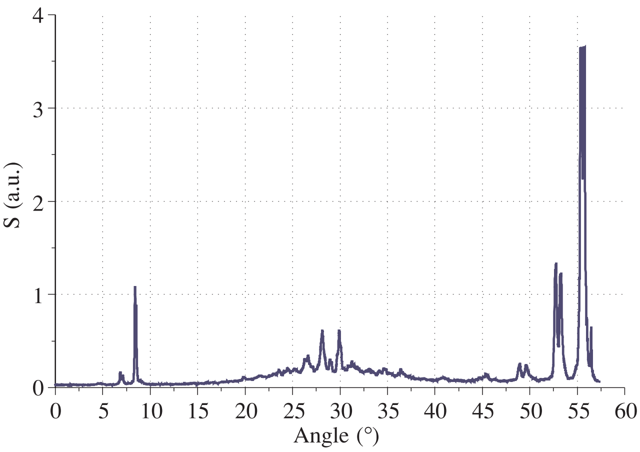

Fig. 5. Mode characteristic of a waveguide with the grating coupler.

6. Results of investigations on grating couplers

In order to continue further attempts to get grating couplers, the previous technological process has been modified several times. The best grating couplers were obtained by means of the following technology. The solutions were prepared in the same proportions as presented in part 1. A partial TEOS hydrolysis lasted 75 minutes. The final solution, after the addition of TET, was obtained after 3 hours of mixing it in an ultrasonic washer at 60ºC. From this solution the waveguide layers were extracted and deposited on glass substrates. Next, the structures of the grating couplers were imprinted by means of the designed imprinting system. Twenty grating couplers were obtained on twenty different substrates with a deposited waveguide layer of the same sol-gel solution, as presented in part 1. The imprinting processes were started 2 minutes after the removal of the cover glass plate from the sol-gel solution. Investigations of previous grating couplers have shown that the grooves in the grating couplers are too shallow and the surface of the gratings are considerably deformed. During these processes, the imprinting pressures were by one order higher than the preceding ones (above 1 MPa). The obtained samples were divided into three similar series, differing in temperature and the time of their heating. The samples have been kept at the temperatures of 200°C, 250°C, and 300°C for 3, 2.5, and 2 hours, respectively.

Due to the fact that the TE_o and TM_o modes propagating in the structure display various effective propagating constants, various synchronous angles (angles of incidence of the laser beam on the structure, at which the appropriate mode is excited) are observed for various modes. The structures of grating couplers were tested in the system presented in Fig. 3. Preliminary measurements have made it possible to find out that the structures of the grating couplers were characterized by much better optical properties when they were produced with a pressure of about 1.5 MPa.

Figure 6 illustrates the characteristics of the selected grating coupler obtained on planar waveguides applying the sol-gel method. For this purpose a pressure of the order of 1.3 MPa was exerted. After imprinting, the samples were kept for 3 hours at a temperature of 250°C.

As Fig. 6 shows, in planar waveguides, obtained by means of the sol-gel method, the zero order mode (TE_0 and TM_0) and first-order mode (TE_1 and TM_1) can propagate. For the same order of mode, the effective propagation constant of the TE_i mode is smaller than for the TM_i mode. Therefore TE modes are excited at smaller values of the incident angle than TM modes. In the waveguide structure, excited by means of a grating coupler, only one mode can propagate at a given angle of incident light.

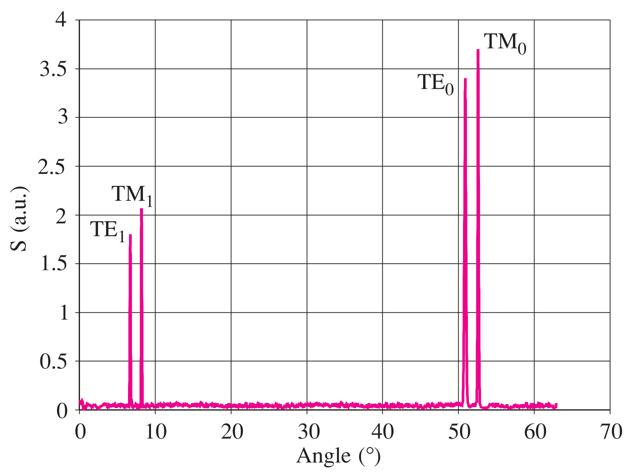

Fig. 6. Mode characteristics of a grating coupler.

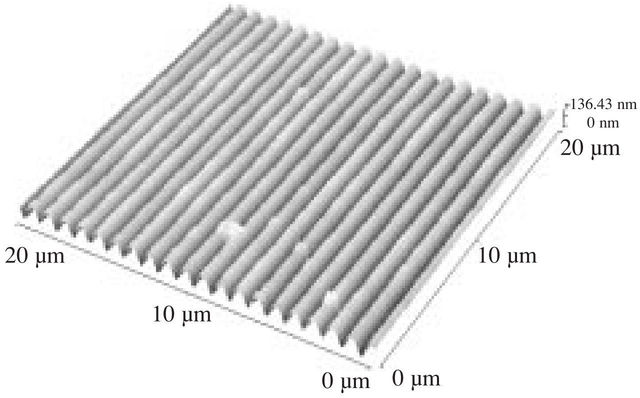

Fig. 7. Periodical grating coupler structure (image by an atomic force microscope).

Figure 7 shows the image of the grating coupler, obtained while using the microscope of atomic forces (AFM).

During the measurement, the humidity in the laboratory compartment was nearly equal to 30%. The investigations have shown that the angles Θ_i at which the modes are excited in the waveguide by means of a grating coupler depend on the ambient atmosphere.

The investigations have also shown that the TM modes are more sensitive to alterations of external conditions than TE ones.

7. Influence of ambient humidity on propagation of light in a waveguide structure with a grating coupler

Figure 8 presents the mode characteristics of the same structure, but when during the measurements the humidity in the laboratory compartment was nearly equal to 100%.

The characteristics of the TM_0 modes, obtained in the conditions of 30%, 60%, and 100% of ambient humidity are to be seen in Fig. 9.

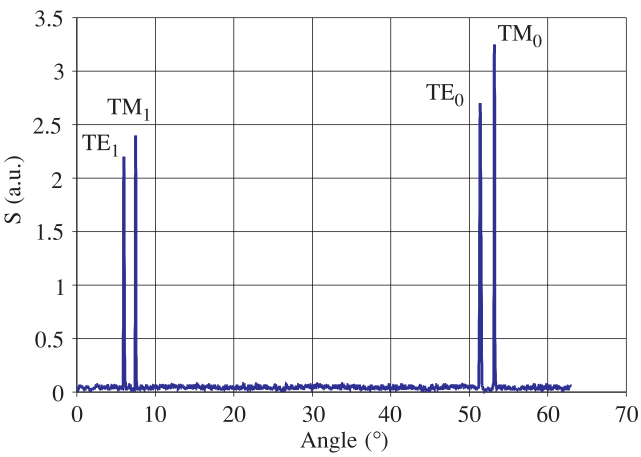

Fig. 8. Mode characteristics of a grating coupler (for 100% environment humidity).

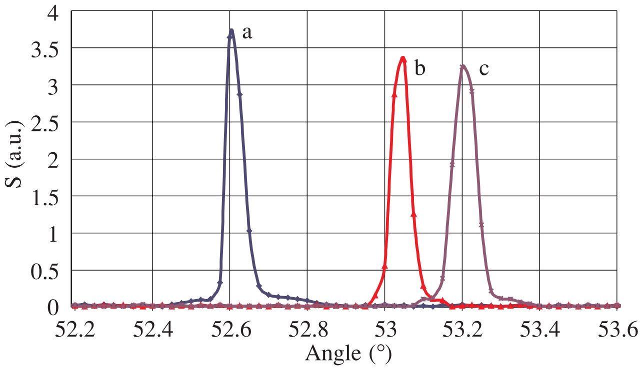

Fig. 9. Mode characteristics of TM_0 for: a) 30%; b) 60%; and c)100%; of environment humidity.

In such cases, the mode characteristics are different. The angles at which the light can be introduced into the structure change due to the ambient humidity. The intensity of the propagated modes has changed, too.

8. Conclusions

The investigations have shown that grating couplers and single-mode waveguides can be obtained in the course of one technological process. In result of these investigations, the parameters of the process were determined, in which it is beneficial to produce periodical structures by mechanical impressing the pattern of the mask on the surface of the waveguide. Experimental investigations have been carried out concerning the influence of the stress exerted in a specially designed system of imprinting the pattern of the mask on the waveguide substrate upon its optical properties and the geometrical shape of the structure, as well as on the degree of its damage. The mechanical pressure permitting the performance of high-quality periodical structures exerts a stress of the order of 1.5×10^6 Pa.

The investigations have shown that the technological conditions of grating couplers performance decided greatly about the optical properties of those structures, both the energy guided modes and the generation of undesirable modes. The mechanical imprinting of grating couplers on planar waveguides, obtained by means of the sol-gel method, requires strict technological regimes. The production of waveguides by means of the sol-gel method for sensor applications is technologically not so rigorous.

One ought to admit that the production of the waveguides and grating couplers is realized in one technological process. It is very important for the application of planar and strip waveguides for sensors. Broad possibilities of their applications result from the low cost of their production and easy modification of their sensor properties by means of deposition of various sensor layers on them.

A grating coupler in form of a periodical structure on the waveguide surface displays a high selectivity of the coupling angle, whereas in the case of applying a prism as a coupler the angle at which the coupling of the laser beam to the waveguide is observed, amounts to several degrees; in the case of well-made grating couplers this angle range does not exceed ten arc minutes.

In the course of our investigations we could observe that even a small change in the composition of the atmosphere surrounding the structure effects a change of the angle of coupling. This is an essential and very favourable property of the structure from the point of view of applying grating couplers in sensors.

The assessment of the results of these investigations leads to the conclusion that the developed grating couplers are characterized by a high effectiveness of coupling, amounting to some tens of percents. Such couplers will be applied in gas sensors, including sensors of toxic industrial substances.

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