A plasmonic switch using metal-insulator transition in VO_2

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We report on the design of a plasmonic switch using phase transition phenomena of a metal-dielectric-metal waveguide. The proposed switch uses vanadium di-oxide material, which undergoes phase transition from semiconducting to metallic phase around at 68^0C. The on and the off states of the switch correspond to the absence and presence of voltage applied to this material. The function of this device numerically studied using finite element method (FEM) simulation at the wavelength of 1.55 μm. We obtained a modulation depth of 40 dB for a device length, thickness and width of 0.50 μm, 0.1 μm and 0.3 μm, respectively. We show that how the dielectric films thickness, length, width and the wavelength of the incident light affect the modulation depth. The supporting modes and the relative losses for the given structure are also studied.

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1. Introduction

The need for nanoscale optical devices using plasmonics is increasing. Recent advances in plasmonics have revealed the great potential of metallic nanostructures to bridge the length-scale mismatch between diffraction-limited dielectric optical systems and nanoscale on-chip electronics [1, 2]. Several different nanoscale plasmonic waveguiding structures have been recently proposed, including metallic nanowires, metallic nanoparticle arrays, V-shaped grooves, and metal-dielectric-metal (MDM) waveguides. Among the wave-guiding structures supporting plasmonic mode propagation, those that focus the electromagnetic energy into the dielectric region of a metal-dielectric-metal (MDM) configuration allow for subwavelength light propagation. MDM- based plasmon slot waveguides have been shown to provide both long range propagation and subwavelength spatial confinement [3]. Thus, MDM waveguides could be potentially important in providing an interface between conventional optics and subwavelength electronic and optoelectronic devices.

Active plasmonic devices with an externally controlled response are critically important to the successful introduction of plasmonics for on-chip applications. Several different approaches have been proposed in order to achieve active control of light in nanoscale plasmonic devices. These include thermo-optic [4], magneto-optic [5], electro-optic [6], elasto-optic [7] and gain media [8] in plasmonic devices to change the effective refractive index. An alternative approach for active control of optical signals in plasmonic devices is a reversible insulator-to-metal phase transition under an applied electric field or by direct heating.

The phase transition of the crystalline vanadium dioxide (VO_2) occurring has been of interest in recent years for its potential applications in active optical devices. Monophase VO_2 can be transformed from a relatively transparent insulating state with monoclinic crystal structure to a metallic rutile phase upon application of thermal, optical or electrical stimuli. An abrupt metal-insulator transition was observed in VO_2 thin films during the application of a switching voltage pulse over a threshold voltage of 7.1 V at room temperature [9]. A novel thermally controlled optical switch based on VO_2 thin film has been fabricated with typical transition temperature at 68^0C [10]. The phase transition has been reported to occur on a time scale of 10^{-8} *sec* under an applied electric field or by direct heating [11].

Recently, thermally controlled plasmon resonance modulation of single gold nanoparticles on VO_2 thin films is reported in which VO_2 film undergoes its insulator to metal phase transition around 67^0C [12] and further, a hybrid silicon–vanadium dioxide (Si-VO_2) electro-optic modulator has also been demonstrated that enables direct probing of both the electrically triggered semiconductor-to-metal phase transition in VO_2 and the reverse transition from metal to semiconductor [13]. However, electrically controlled plasmonic switching using VO_2 based MDM waveguide structure is not yet reported. The proposed design structure and optical phenomena is different than proposed by Petr Markov et al [13].

In this paper, we investigate the active plasmonic switching behavior-using VO_2 filled MDM plasmonic waveguides in which the on/off states correspond to the absence/presence of applied DC voltage. Variations in the real and imaginary part of the refractive index of the VO_2

material result in modulation. Finite element method (FEM) simulation results are consistent with our theoretical concept. We discuss the effect of the length, width, thickness and the wavelength of incident light on modulation depth of the VO_2 active film. The proposed design structure is simple and compact.

2. Design structure and theory

Fig.1(a) shows the design structure of the proposed plasmonic switch consisting of a MDM waveguide directly coupled to a cavity filled with an active material of VO_2 whose absorption coefficient can be modified with an external electric field. The width of the MDM waveguide, the thickness of the dielectric film, the thickness of the metal film and the length of the VO_2 film are denoted as *w*, *d*, *t* and *L* respectively.

Fig.1(b) and 1(c) shows a block diagram of two-dimensional view of the proposed design structure. It shows that in the absence of external field light completely passes through the MDM waveguide device. On the other hand when we apply an electric field, light does not pass through the MDM waveguide device due to phase transition of VO_2 material from semiconducting to metallic state.

We show that such a direct-coupled-cavity structure can act as a plasmonic switch, in which the on/off states correspond to the absence/presence of electric field. Variations in the real and imaginary part of the refractive index of the material filling the cavity result in modulation depth. We use a coupled MDM plasmonic waveguide of Silicon (Si) material as a dielectric layer to a cavity filled with an active VO_2 material.

The phase transition occurs via the gradual growth of metallic domains in the film, and the dielectric properties of the film changes in the vicinity of the transition temperature [14]. The phase transition by growth of conductive domains in the plane of the VO_2 thin film can be verified in a quantitative manner using effective-medium theory [15].

The change in temperature with applied voltage across the metal electrode of the MDM waveguide filled with VO_2 material can be expressed as

$$\delta T_C = \frac{(C_M - C_D)V^2}{2(S_M - S_D)} \quad (1)$$

where C_M and C_D are the electrostatic capacitances of the system per unit area corresponding to the metallic and the dielectric states of the vanadium oxide film, respectively and S_M and S_D are their entropies. Further $\delta T_C = T_C - T_{CO}$, T_{CO} is the thermodynamic temperature in the absence of an applied field. The electrostatic capacitance C is defined as $C=\varepsilon A/d$, where, A and d are the area and thickness of the film.

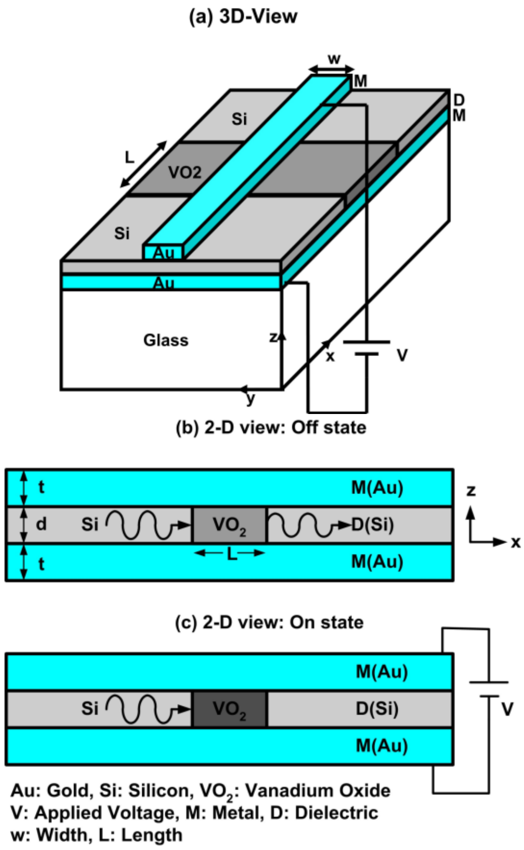


Fig. 1. (a) Three dimensional view of plasmonic switch based on metal-insulator phase transition in VO_2 through a MDM waveguide. (b) Two dimensional view of MDM layered structure in switch-off state: VO_2 is transparent and (c) Two dimensional view of MDM layered structure in switch-on state: VO_2 becomes metallic.

In Fig. 2, we show the change in temperature by applying voltage for VO_2 film using Eq. 1. In the numerical calculation, we have considered $C_M \approx 10^{-2} F/m^2$, $C_D \approx 10^{-6} F/m^2$ and S_M-$S_D \approx 5\times10^{-3}$ J/Km^2 for the given VO_2 thin film, [16]. These numerical values of C_M, C_D and S_M may differ for thick films. The results show that the temperature of the VO_2 film increases in a square manner with increasing the voltage across the metal electrodes. It is shown theoretically here that by the application of 5 V for VO_2 thin films, an increment in the temperature is approximately 49 ^{0}K which may be sufficient for phase transformation above the room temperature.

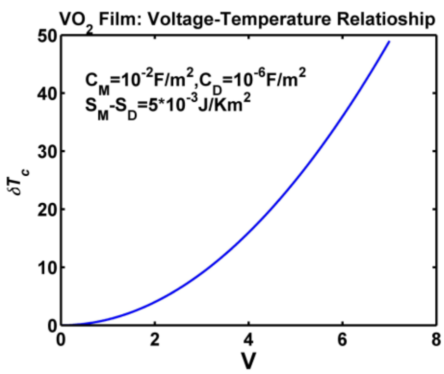


Fig. 2. The variation of temperature with applied voltage for VO_2 film through a MDM waveguide.

2.1 Switching mechanism

At room temperature, the resistivity of VO_2 is nearly equal to that of the Silicon and is transparent to the propagating plasmonic wave through MDM waveguide. If we heat the metal film of MDM waveguide using a micro heater above 68 °C, an abrupt transition may occur to the conductive metallic phase. Monophase VO_2 can be transformed from a relatively transparent insulating state with monoclinic crystal structure to a metallic rutile phase. Upon cooling, the VO_2 film may regain its insulating-phase properties, but at less temperature and thus a hysteresis is expected for films. There are reports on phase transition at room temperature [9]. The field or carrier injection alone may be sufficient to induce the transition. The local power injection due to an applied field can heat the VO_2 grain from room temperature to transition temperature and this transition results most directly from Joule heating. If this is the case then switching operation can be performed at room temperature.

There are two theories for metal-insulator transition. One is the Mott transition that occurs by a change of the electronic Coulomb interaction between electrons [17, 18] the other is the Peierls transition, which is induced by the electron-phonon interaction accompanied with the structural phase transition [19]. The mechanism of both kinds of metal-insulator transition phenomena has been explained well in reference papers [17-19].

2.2 Switching speed

There is no transit time limitation for a current switch based on field-controlled metal insulator transition. One possible upper limit may be due to the speed of lattice relaxation [16]. We believe, however, that a more restrictive limitation is related to the kinetics of the first-order phase transition. The switching speed of the optical switches could be measured by applying a square wave to the micro heater and detecting and measuring the output power simultaneously using a photo detector and a digitizing oscilloscope. The switching time can be speedup by utilizing microbridge structure with smaller thermal mass. The phase transition has been reported to occur on a time scale of 10^{-8} *sec* under an applied electric field or by direct heating.

2.3 Temperature fluctuation

The sharpness and amplitude of the transition and the hysteresis upon heating and cooling strongly depends on crystal structure, grain size, grain boundaries, and defect contents. The width of thermal hysteresis is directly related to $\Delta T_r = 2\gamma/(r_C \Delta S_0)$ [20], where ΔT_r is the deviation from the equilibrium transition temperature, ΔS_0 is the change in entropy between the two phases, r_C is the critical size of stable nuclei and γ is the interfacial energy. Thus, hysteresis increases with decreasing r_C *and* ΔS_0 while it decreases with decreasing γ. The role of grain boundaries can be understood through the interfacial energy.

3. FEM simulation results

To model the proposed plasmonic switching, FEM simulations were done using COMSOL Multyphysics-RF module-Electromagnetic wave analysis. The structures used in the simulations had *t*=50 nm of gold on the top and bottom of the MDM waveguide. The devices were simulated at telecommunication wavelength of 1.55 µm with and without an applied electric field. Scattering Boundary Condition is used for all 3D-FEM simulations. In all simulations, the permittivity of gold is taken from the well accepted experimental data, $\varepsilon = -18 + i11.58$ at the wavelength $\lambda = .55\mu$ [21]. At the wavelength of 1.55 µm, the index of VO_2 is 3.21 + *j*0.17 near room temperature (without voltage) and 2.15 + *j*2.79 when heated to 100 °C (with applied DC voltage), which indicates a clear transition from a nearly transparent state to a phase with metallic optical properties [11]. The transmittance of the structure is defined by $T = P_{out} / P_{in}$. By applying the finite element method, we solve for the *H*-field in the entire structure. H_y field patterns are obtained at the center of the dielectric core in the z-direction, where z = 0. Free mesh subdomain parameters of metal and dielectric regions are 1µm and 0.1 µm, respectively.

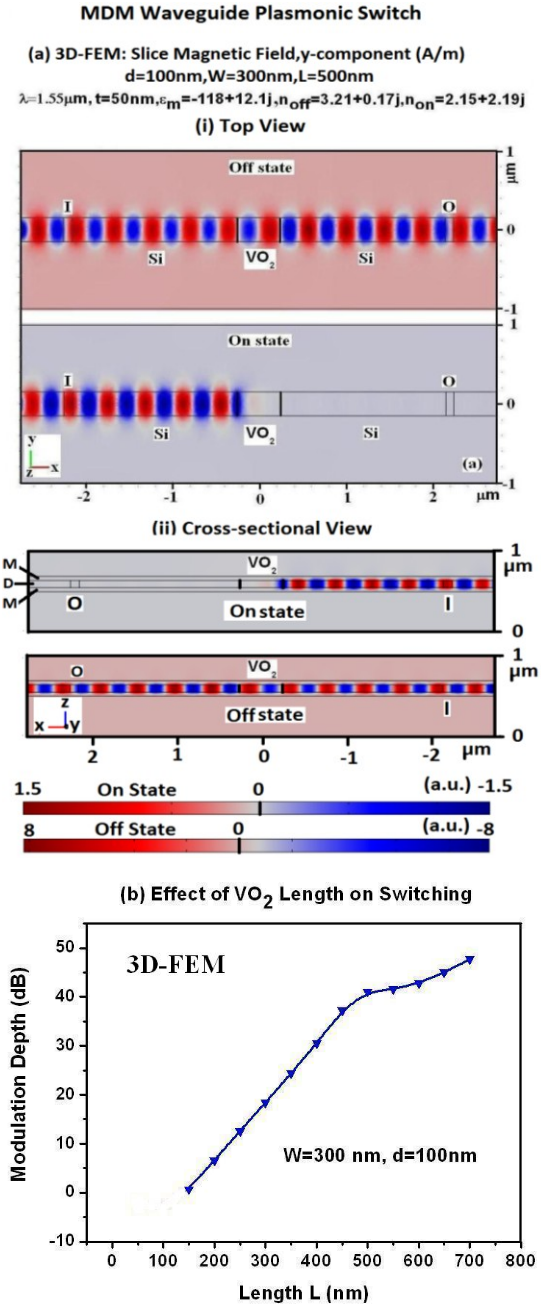
First of all we study the plasmonic waveguiding properties in terms of supporting modes and relative losses for the considered MDM waveguide structure using 2-D FEM simulation. Table 1 shows the real and the imaginary value of effective refractive index for different TM-modes at room temperature. TE mode does not exist as thickness of the waveguide is too small (~d=100 nm). Higher order TM-mode may exist due to relatively larger width (~ W=300 nm) of the waveguide. This result shows that the real part of the effective refractive index decreases abruptly with TM mode number where as imaginary part increases slightly and then decreases slightly with mode number. The imaginary part of effective refractive index represents the corresponding relative losses of the given mode. Effectively only fundamental and first TM mode exists for the assumed structure in which fundamental mode exhibit higher effective refractive index and therefore in all subsequent 3D-FEM simulation results only fundamental mode is considered. Higher order TM mode will exist for much larger width of the MDM waveguide.

Table 1. 2D-FEM Simulations: Supporting modes and relative losses.

S. No.	TM Mode Number	Real part of effective refractive index (n_R)	Imaginary part of effective refractive index (n_I)
1	0	3.431197	0.172736
2	1	2.695673	0.191926
3	2	1.505556	0.152856
4	3	1.492284	0.147097

In Figs. 3 (a) we show the top view and the cross sectional view of the magnetic field profile of the proposed plasmonic switch using 3D-FEM simulations corresponding to the off and on states, respectively. In the absence of an applied voltage, corresponding to the off state, the VO_2 cavity is in semiconducting state and is transparent to the incident optical mode.

In contrast, in the presence of an applied voltage, corresponding to the on state, the transmission decreases abruptly leading to a large modulation depth. This is a favorable situation for an ideal optical switch. To visualize the wave propagation, simulations are conducted for both the switch-off and switch-on states. The cross-sectional view shows that most of the energy is confined in the dielectric region and the top view shows that energy does not spread beyond the MDM waveguide. The arbitrary unit (a. u.) is chosen to measure the magnetic field intensity.



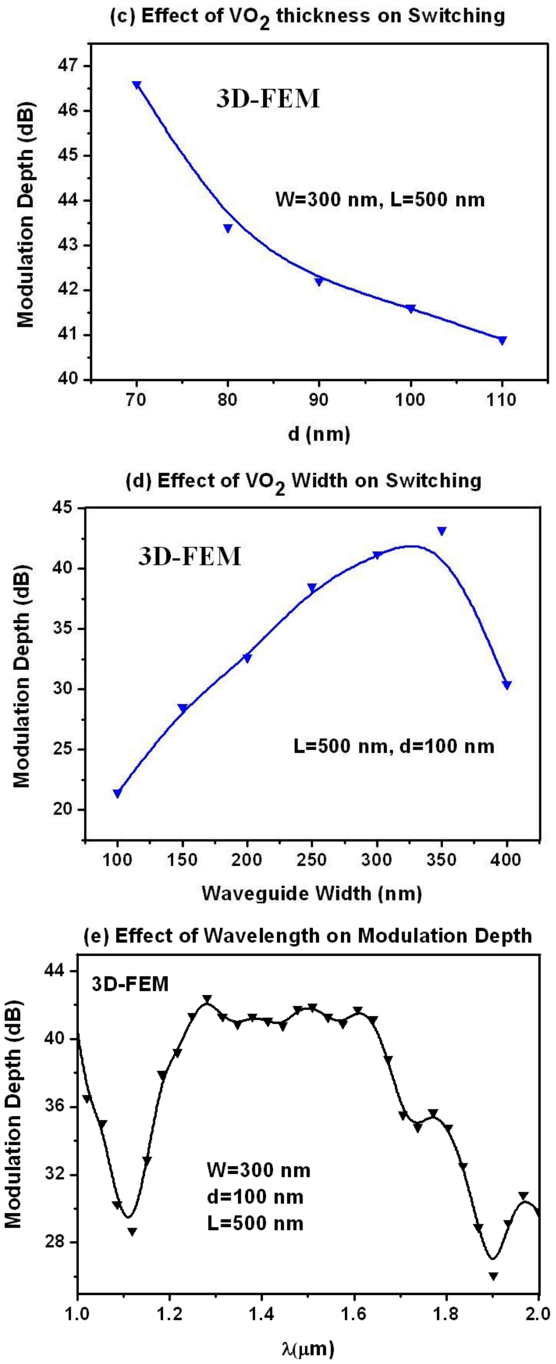


Fig. 3. 3D-FEM simulation results (a) shows the magnetic field profile of the switch for L=500 nm, W=300 nm, t=30 nm and d=100 nm in switch-off and switch-on state at the wavelength of 1.55 μm (b) Modulation depth as a function of length L. (c) Modulation depth as a function of dielectric film thickness d. (d) Modulation depth as a function of dielectric film width W. (e) Modulation depth as a function of wavelength of the incident light λ. Other parameters in (b), (c), (d) and (e) are same as in (a).

In Fig. 3 (b) we numerically study the modulation depth of the proposed plasmonic switch as a function of the cavity length L for a given width W=300 nm and thickness d=100 nm using 3D-FEM simulation. The modulation depth in dB can be defined as 10 log {T (n =

3.21 + 0.17*j*)/*T* (*n* =2.15 + 2.79*j*)}, where *T* is the transmission ratio. We observe that the modulation depth increases with the cavity length *L*. The increase is almost exponential with slight oscillations associated with the Fabry-Perot response in the on state. We cannot increase the length much because device loss increases by increasing the cavity length.

In Fig. 3 (c) we numerically study the effect of dielectric film thickness on the modulation depth for a given length *L*=500 nm and width *W*=300 nm of the device using 3D-FEM simulation. We observe that modulation depth decreases as the thickness of the dielectric film *d* increases. We believe that this is due to the fact that the effective refractive index in MDM plasmonic waveguide increases as the thickness of the dielectric film decreases [7]. We cannot increase the thickness much as the roll of surface plasmonic wave will reduce through MDM waveguide.

In Fig. 3 (d) we numerically study the effect of dielectric film width on the modulation depth for a given length *L*=500 nm and dielectric thickness *d*=100 nm using 3D-FEM simulation. We observe that modulation depth increases as the width of the dielectric film *W* increases up to certain extent. This is because the fundamental mode is better confined by increasing the width and effective refractive index increases with waveguide width [22]. Beyond a certain extent, the modulation depth starts decreasing with increasing the width. This is due to the fact that higher order modes of low effective index may exist which possesses smaller effective index. In parallel the metallic losses increase due increase in the width of the metal film.

In Fig. 3 (e) we show the effect of modulation depth on wavelength of the incident light from 1.0 μm to 2.0 μm using 3-D FEM simulations. It is shown that modulation depth increases from 28 dB to 42 dB with increasing the wavelength from 1.1 μm to 1.3 μm of incident light and then it is approximately constant up to 1.62 μm. Further by increasing the wavelength of the incident light from 1.62 μm to 1.82 μm, the modulation depth decreases from 42 dB to 28 dB. From the Drude Model, it is known that the dielectric constant of the metal changes with the wavelength and therefore in this study, we have considered the dielectric constant at the wavelength equal to 1.5 μm of gold which is in the mid of the wavelength range.

4. Discussion

Active plasmonic devices based magneto-optics [5], electro-optics [6] or a MOS field-effect modulation [23] possesses high switching speed but low a low modulation depth. On the other hand, the active plasmonic devices based on thermo-optic effect [4] and liquid crystal [24] possesses high modulation depth but a low switching speed. The proposed active plasmonic device can have both a high modulation depth and a high switching speed. The proposed switch can find use in electronic as well as optical circuits. Optical application is based on the dramatic change in the imaginary part of effective refractive index of plasmonic MDM waveguide accompanying the VO_2 material. The dimensions mentioned in this study are possible to fabricate with available lithographic techniques. The modulation of light through nanohole arrays in metal/VO_2/glass film has been demonstrated [25]. Thus deposition VO_2 on metals is doable and the proposed device concept can be used in the real world. Our numerical results show that a modulation depth approximately 40 dB is possible to design with dimensional size of 0.50× 0.1× 0.3 μm^3. The phase transition may occur on a time scale of micro to nano second, under an applied electric field or by direct heating. In addition, we estimate that the electrical power will be less due to the nanoscale size of the device. These figures of merits designate that the proposed device could be useful for nanophotonic integrated circuit. The main contribution of the proposed study is its high modulation depth and its ultracompact size. In addition, the design structure is simple and VO_2 material is introduced in such a design structure.

We also note that, in addition to the VO_2 material, other materials based on semiconductor to metal phase transition such as *W* doped VO_2 [26], chromium nitride [27] can be used. To avoid the dielectric breakdown, one has to take an appropriate thickness of the dielectric film. From the simulation results, it is evident that further improvement in the performance of the device is possible with optimizing the design structure i.e. by taking an appropriate thickness, width and length of the VO_2 film. Note that placing the proposed plasmonic switch within waveguide appeared to decrease the insertion loss of the device compared to the higher insertion losses determined from external insertion of the device into the waveguide. We have not emphasized much on theory of phase transition phenomena in VO_2 material as this is well known and have been reported [9-15, 17-19 and 25] for different applications. Rather we have emphasized much on the application of phase transition phenomena for plasmonic switching through a MDM waveguide.

Recently, other researchers have also reported the modulation phenomena based on meta-insulator transition in VO_2 [28, 29], however present modulator is different in a manner that this modulator is inbuilt within waveguide and therefore, we expect less coupling loss with external waveguide. Further, it is evident that thermal excitation, optical excitation, electrical excitation, doping, or strain engineering can trigger phase transition in VO_2; however, we take the choice of electrical excitation in the presented design structure [29] and more explanation is given in Eq. (1).

5. Conclusion

We have theoretically investigated and numerically analyzed a plasmonic switch using phase transition phenomena of VO_2 material based on metal-dielectric-metal waveguide. The device structure is simple with high switching performance. The modulation depth increases with the length of the proposed device. On the other hand, the modulation depth decreases with the thickness of the dielectric film. In case of modulation depth dependence on waveguide width, it increases up to some extent and then it decreases with further increment in the waveguide width. For the considered design structure, only fundamental mode exists effectively. FEM simulation results are consistent with theoretical concept. We believe that the device presented in this paper has an extensive potential in nanoscale integrated optical circuits.

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