https://doi.org/10.48048/tis.2022.1721

Gold Coated VO_2 Nanogratings Based Plasmonic Switches

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Received: 4 March 2021, Revised: 8 August 2021, Accepted: 12 August 2021

Abstract

This paper presents 2 dimensional (2D) and 1 dimensional (1D) gold (Au) coated VO_2 (Vanadium Dioxide) nanogratings based tunable plasmonic switch. VO_2 is a phase changing material and hence exhibits phase transition from semiconductor to metallic phase approximately at 67 ºC or 340 K (critical temperature) which can be achieved by exposure to IR radiation, application of voltage, heating, etc. and there is a huge contrast between optical properties of its metallic and insulating phases and hence that can be utilized to implement VO_2 based optical switches. These VO_2 based gratings couple the incident optical radiation to plasmonic waveguide modes which in turn leads to high electromagnetic field enhancement in the gaps between the nanogratings. The proposed Au coated VO_2 nanogratings can be fabricated by using current state of art fabrication techniques and provides switchability of the order of femtoseconds. Hence the optical switching explained in our paper can be used fast switching applications. For an optimum switch our aim is to maximize its differential reflectance spectra between the 2 states of VO_2, i.e., metallic and semiconductor phases. Rigorous Coupled Wave Analysis (RCWA) reveals that wavelengths for maximum differential reflectance can be optimized over a large spectral regime by varying various parameters of nanogratings for example groove height (h), width (w), gap (g) between the gratings, and thickness (t) of Au coating over VO_2 by simulation using RCWA for maximum differential reflectance between VO_2 metal and semiconductor phase, i.e., the switching wavelengths can be tuned by varying grating parameters and thus we can have optimum optical switch.

Keywords: Gold, Nanogratings, Plasmonics, Switching, VO_2

Introduction

Switches are the key components of any network and form the essential functionality of any telecommunication network. Optical switches are integral part of optical network and broadly can be classified in to 2 categories the OEO (Optical to Electrical to Optical) and the OOO, or all-optical switch. In 1st type of switch, signal is converted to electrical form for switching whereas in 2nd one signal is kept in optical form only. OEO is a lossless unidirectional switch on the other hand OOO is a lossy switch which is bidirectional in nature. Many types of optical switches are available like MEMS [1] in which switching is done by employing some mechanical means like mirror, directional coupler and are used in applications like displays, sensors, etc. These switches are easily scalable but are limited in terms of durability. In electro-optic switches, we use highly birefringent substrate material like Lithium Niobate ($LiNbO_3$) for switching [1,2]. These switches are quiet fast and reliable but their performance is limited by high insertion loss and polarization dependency. In thermo-optic switches utilizing thermo-optic effect [3], we have interferometric and digital optical switches. In case of displays we use LCD (Liquid Crystal Display) switch which uses different polarization states of light for switching purpose [4]. Many more optical switches include Bubble switch [5], Acousto-Optic switch [6], Semiconductor Optical Amplifier switches [7] and Fiber Bragg Grating based switches [8].

Plasmonics, highly dynamic field merging electronics and photonics at nanoscale dimensions introduced us to a new generation of on chip, fast nanoscale devices having unique properties. Plasmonic switches forms the fundamental block of any nanophotonic circuit. They provide ultracompact size, low power consumption, high bandwidth and ultrafast switching. Plasmonic switches combines the localization of electronic waves with the propagation properties of optical waves and hence plasmons achieve large field confinement. For active plasmonic switches we need a plasmonic waveguide technology and control of active area is required. Simplest plasmonic waveguide structure that provides switching is MI (Metal-Insulator) interface which strongly confines the field at the interface and then field decays exponentially as the distance from the interface increases but propagation length is of order of few tens of µm. Another plasmonic waveguide is MIM (Metal-Insulator-Metal) stack. Both these structures are required to obtain a balance between high field confinements and optical losses which is achieved by proper designing [9,10]. Many types of plasmonic switches have been demonstrated in literature. In thermo-plasmonic switches main principle is the fact that heating wire act as a plasmonic waveguide and heating induced refractive index variation is responsible for confinement of SPP mode [11,12]. These switches have moderate switching time with high extinction ratio but have high power consumption. Plasmonic switches based on Pockel effect which is responsible for the variations in refractive index provides high data rate and are based on MIM structure [13]. Phase change effect can be utilized for plasmonic switching and we utilize phase transition property of certain materials on external stimulus such as heating, application of voltage/current etc. In this paper we have proposed plasmonic nanogratings both 2D and 1D for optical switching having grating w, the g, the h and the t of the Au layer, as shown in **Figures 1**(**a**) and **1**(**d**) respectively. Plots for reflectance spectra for both states of VO_2, i.e., metallic and semiconductor and differential reflectance plot against wavelength of 2D nanogratings is shown in **Figures 1**(**b**) and **1**(**c**). Similar plots for reflectance spectra and differential reflectance of 1D nanogratings is shown in **Figures 1**(**e**) and **1**(**f**).

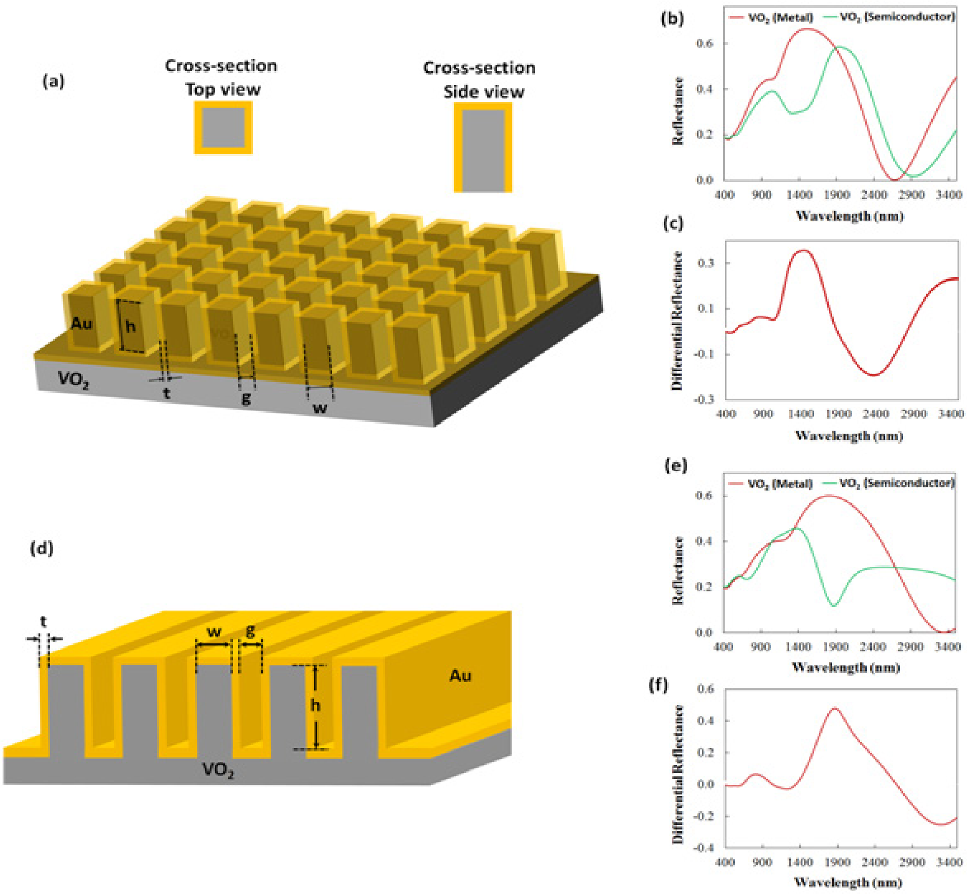

Figure 1 (a) schematic for 2D VO_2 nanograting coated with a thin layer of Au showing the grating w, the g, the groove h and the t of the Au layer, (b) reflectance versus wavelength curve for VO_2 (S), i.e., RS (λ), and VO_2 (M), i.e., RM (λ) for 2D nanograting generated using RCWA simulations, (c) differential reflectance for 2D nanograting, (d) schematic for 1D VO_2 nanograting coated with a thin layer of Au showing the grating w, the g, the groove h and the t of the Au layer, (e) reflectance versus wavelength curve for VO_2 (S), i.e., RS (λ) and VO_2 (M), i.e. RM (λ) for 1D nanograting generated using RCWA simulations and (f) differential reflectance for 1D nanograting coated with a thin layer of Au.

VO_2 is an attractive material having phase transition property and demonstrates immense potential as a phase change material (PCM) [14]. VO_2 is a transition metal oxide possessing narrow d-electron bands having correlated electron system which is quiet sensitive to changes in extrinsic parameters. VO_2 is a strongly correlated oxide that undergoes 1st order phase transition from insulator to metal around 67 ºC and hence termed as smart material [15,16] that respond to external stimuli may be temperature, magnetic or electric field, pressure, current, etc., and hence shows a reversible phase transition that results in variation of electrical and optical properties. Phase transition in VO_2, thus forms the core or heart of VO_2 properties and attracting attention and are of technological importance for optical and electrical applications as reported by Morin in 1959 [15]. This phase transition from insulator to metal changes its crystallographic structure from monoclinic to rutile which in turn provides variation in electrical and optical properties of material. This phase transition is quite fast and reversible and hence provides ultrafast switching. Transition temperature may be altered by doping VO_2 with other metals [17] and other oxides of VO_2 like VO, V_2O_3 and V_2O_5 also exhibit phase transition [17], but in case of VO_2 this phase transition is near room temperature and further may be altered by doping. VO_2 is a promising candidate for application in Photonic Integrated Circuits as its compatible with CMOS [18]. Many active optical devices based on VO_2 have been proposed in literature [19-23]. For the 1st time, VO_2 gratings coated with Au has been demonstrated for the optical switching because of following reasons. Firstly, most of past work done was based on either propagating surface plasmons or localized plasmon resonances but in our case, Au coated VO_2 nanogratings or plasmonic nanostructures have been used that employ plasmonic waveguide modes. For the very 1st time 2D nanogratings have been demonstrated. Secondly most of the past work was experimental and no numerical modelling work involving 2D VO_2 nanogratings coated with Au exist in the literature. Moreover, in our case, we can have normal incidence as we do not require angle dependent coupling mechanism like Kretschmann [24] for the coupling of light for the nanogratings. Additionally, in our structure we are having the coating of Au over VO_2 gratings which is more practical from fabrication point of view as during annealing polycrystalline Au is grown over crystalline VO_2 gratings whereas the previous work reported by Sharma *et al*. [25] has the Au gratings with coating of VO_2 and in that case forming a polycrystalline Au coating over VO_2 gratings is not advisable as Au coating forms nanospheres. So in case of our work practically feasible efficient optical switches are proposed.

In the proposed Au coated VO_2 nanogratings, g between the adjacent VO_2 pillars is smaller than the wavelength of incident light so we have plasmonic waveguide mode, i.e., incident light is coupled in to plasmonic waveguide modes resulting in dips in reflectance spectra of VO_2 nanogratings in semiconductor and metallic states. These dips corresponds to resonance wavelengths which provides tunability for switching applications. In the proposed Au coated VO_2 nanogratings when there is a phase transition of VO_2 from semiconductor to metal state, reflectance spectra changes due to change in the structure and thus electrical and optical properties of material which in turn changes the resonance wavelengths. For estimating switching efficiency of the proposed structure, we calculate the differential reflectance of VO_2 in both the states by subtracting the reflectance spectra of VO_2 (M) from VO_2 (S). Best switching is obtained for the maximum values of this differential reflectance. In differential reflectance various dips corresponds to wavelengths for which we can have tunability.

Numerical modelling using RCWA

RCWA [25] was used for calculating the optical properties of the nanogratings proposed in this paper (i.e., the Au coated VO_2 nanogratings). The RCWA is a semi-analytical method based on Floquets theorem [25] which uses a commercially available software called DiffractMOD by Synopsys RSoft Solutions. We have simulated Au coated VO_2 nanogratings for differential reflectance spectra versus wavelength. We have obtained the dielectric constant of metallic and semiconductor phase of VO_2 by fitting the Lorentz model to the dielectric constants given by Verleur *et al*. [26] and dielectric constant for Au were determined on basis of Lorentz Drude model [27]. In the numerical simulations using RCWA for Au coated VO_2 nanogratings, we have varied various parameters of the nanogratings like w of the VO_2 nanogratings, h of the VO_2 nanogratings above the substrate, g between nanogratings or groove width and t of the Au layer coated over VO_2 nanogratings. In this paper, we study the effect of varying nanopillar w from 25 to 150 nm, and varying g, i.e., the g between nanogratings from 5 to 20 nm on the reflectance vs. wavelength curves. The h of the VO_2 nanogratings above the substrate surface, i.e., h is varied from 50 to 250 nm. Nanograting is covered with Au layer, whose t was varied from 2 to 10 nm to observe the effect of varying t on reflectance curves of VO_2 (S) and VO_2 (M). We have obtained differential reflectance curves as a function of wavelength for all the above cases. For all the simulations polarization of all the incident radiation is taken as TM polarization for all the calculations.

Results and discussion

In this section, we analyze the effect of the grating parameters on the magnitude of switchability - provided by 2D and 1D Au coated VO_2 nanogratings - as well as on the wavelengths at which these optically switchable nanogratings can be utilized. The switching property of the proposed Au coated VO_2 nanogratings can be observed by measuring the reflectance of the structure for both the metallic and the semiconductor phases of the VO_2 nanogratings and calculating the differential reflectance spectra between the VO_2 (M) phase and the VO_2 (S) phase. As discussed already, there is an existence of plasmonic waveguide mode localized in the groove depth, i.e., g between the Au coated VO_2 naogratings. The effect of changing the nanograting h, w, g between nanogratings and the t of the Au layer are analyzed in the following sections for both 1D and 2D nanogratings based switches.

Effect of height or nanogroove depth of 2D nanogratings

RCWA simulations were employed to calculate the effect of h, i.e., groove depth of 2D nanogratings. Differential reflectance spectra provide the wavelength and magnitude of switchability. Effect of changing h of 2D Au coated VO_2 nanogratings is shown in **Figure 2**. It can be seen that as h increases, multiple dips in the reflectance spectra are present, which correspond to different plasmonic waveguide modes. It can be seen that there are more number of plasmonic waveguide modes as h increases or in other words increasing h supports localization of multiple plasmonic waveguide modes inside nanogrooves. From the differential reflectance curves, we can observe that for higher values of nanograting h, the number of wavelengths corresponding to maxima or minima of differential reflectance increases, which clearly indicates that we can have switching at multiple wavelengths corresponding to the different plasmonic modes modes.

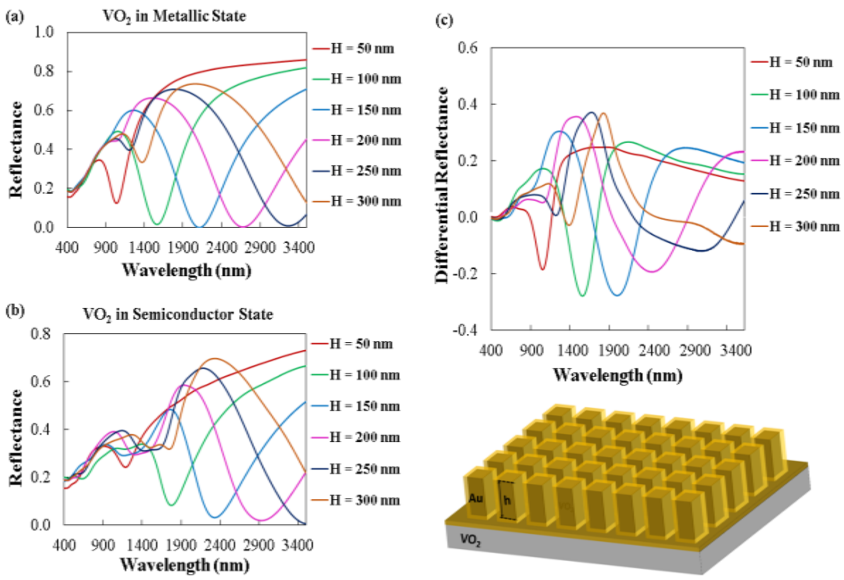

Figure 2 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (2D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (2D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (2D) nanograting. For all the above cases, t = 8, g = 10 and w = 100 nm were taken.

Effect of thickness of Au coating of 2D nanogratings

In addition to the effect of the h of 1D nanogroove on switchability we explored the effect of t of Au coating (2 to 10 nm) as shown in **Figure 3**. For the metallic state of VO_2, as the t of Au coating decreases, it leads to an increase in the volume of the metallic VO_2 (which is a more lossy metal as compared to Au) present in the 2D nanogratings relative to the volume of Au. This leads to an increase in the damping, which is reflected in the broadening of reflectance curves with a decrease in t. There is some broadening of the plasmonic waveguide mode for VO_2 (S) also as the as the t of Au coating decreases as VO_2 (S) also has a large imaginary part of the dielectric constant.

Effect of gap between nanogrooves of Au coated 2D nanograting

Effect of changing the g between the nanogroove is analyzed in this section as shown in **Figure 4**. With a decrease in the g, there is a redshift in the reflectance spectra for both the metallic and the semiconductor states of the VO_2 as decreasing the distance between the opposite walls of nanogrooves reduces the restoring force, and hence reduces the plasmon resonance frequency. Hence, the plasmon resonance related dips in the reflectance spectra occur at higher wavelengths for smaller values of g (i.e., a redshift). Hence tuning g between the nanogrooves will tune the wavelength of the maximum differential reflectance, and thus offers opportunity for design of switchable device over a wide wavelength spectrum.

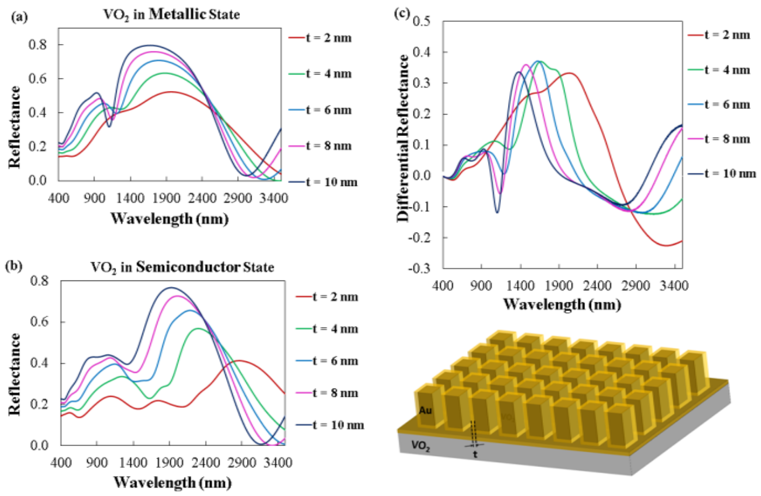

Figure 3 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (2D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (2D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (2D) nanograting. For all the above cases, g = 10, h = 200 and w = 100 nm were taken.

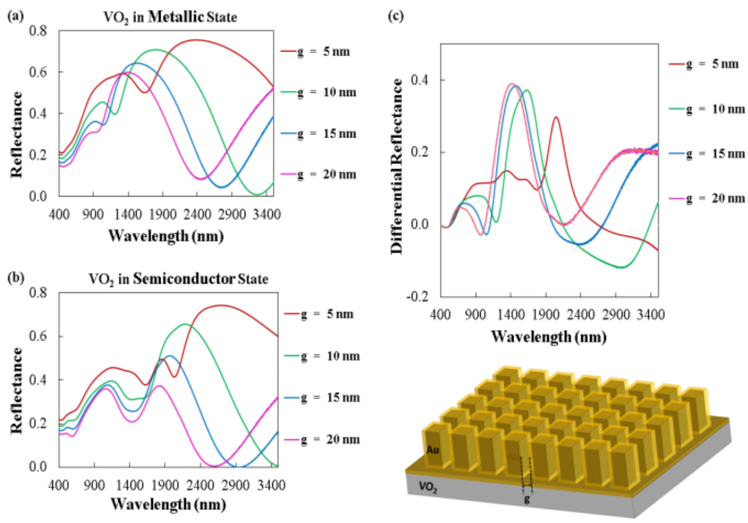

Figure 4 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (2D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (2D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (2D) nanograting. For all the above cases, t = 8, h = 200 and w = 100 nm were taken.

Effect of width or periodicity of 2D nanogratings

In this section we have explored effect of grating w or periodicity of nanograting on the wavelengths of switching as well as magnitude of switching as shown in **Figure 5**. As the w increases, there is a redshift in the plasmon resonance wavelengths associated with the Au coated VO_2 nanogratings for both the metallic and the semiconductor states of VO_2. Therefore, there is a redshift in the peaks in the differential reflectance spectra with an increase in the w.

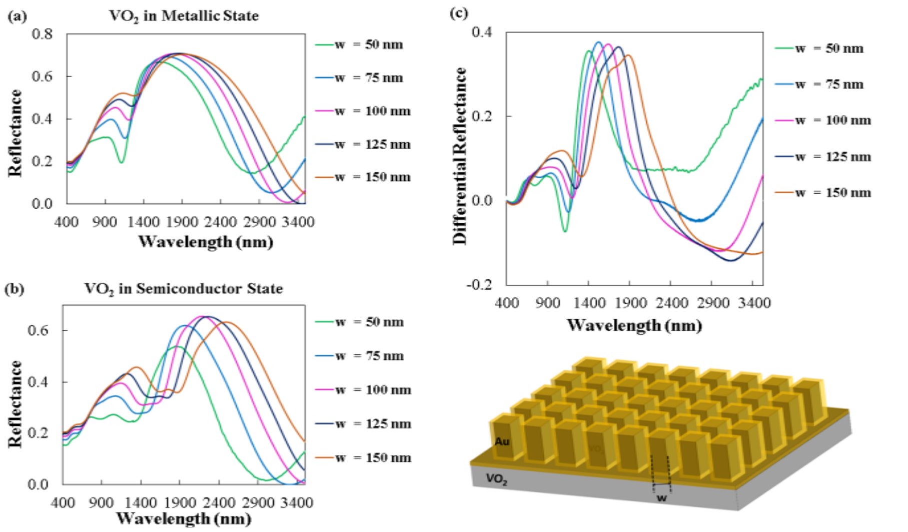

Figure 5 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (1D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (1D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (1D) nanograting. For all the above cases, t = 8, g = 10 and h = 200 nm were taken.

Effect of grating parameters, i.e., height or nanogroove depth, thickness of Au coating, gap between the nanogrooves and width or periodicity of 1D nanogratings

2D nanogratings discussed till now in this paper are periodic in X as well as Y direction. Effect of variation with h of nanograting, t, g and w are shown in **Figures 6 - 9** respectively. Observations and trends on varying the different parameters (h, t, g and w) are similar for 1D as we have observed in case of 2D. As the h of the 1D plasmonic nanogratings is increased, the incident light can effectively get coupled into a greater number of plasmonic waveguide (MIM) modes formed by the Au coated nanogratings. Hence, optical switching using these plasmonic nanogratings can be carried out at multiple wavelengths.

For the metallic state of VO_2, as the t of Au coating decreases, it leads to an increase in the volume of the metallic VO_2 (which is a more lossy metal as compared to Au) present in the 1D nanogratings relative to the volume of Au (**Figure 6**). This leads to an increase in the damping, which is reflected in the broadening of reflectance curves with a decrease in t. There is some broadening of the plasmonic waveguide mode for VO_2 (S) also as the as the t of Au coating decreases as VO_2 (S) also has a large imaginary part of the dielectric constant. As the g between the nanogratings is decreased, the distance between the adjacent plasmonic nanograting walls also decreases, thereby leading to a decrease in the restoring force acting on the conduction band electrons of the plasmonic materials. This results in a decrease in plasma frequency, which in turn leads to an increase in the plasmon resonance wavelength associated with the nanogratings (**Figure 6**). Optimal width of the 1D plasmonic nanogratings (for which maximum differential reflectance amplitude is obtained) can be determined and we can design an optimal ultrafast optical switch (**Figure 6**). The current state of art nanofabrication techniques and film deposition techniques can be employed for fabricating these proposed nanogratings both 1D and 2D.

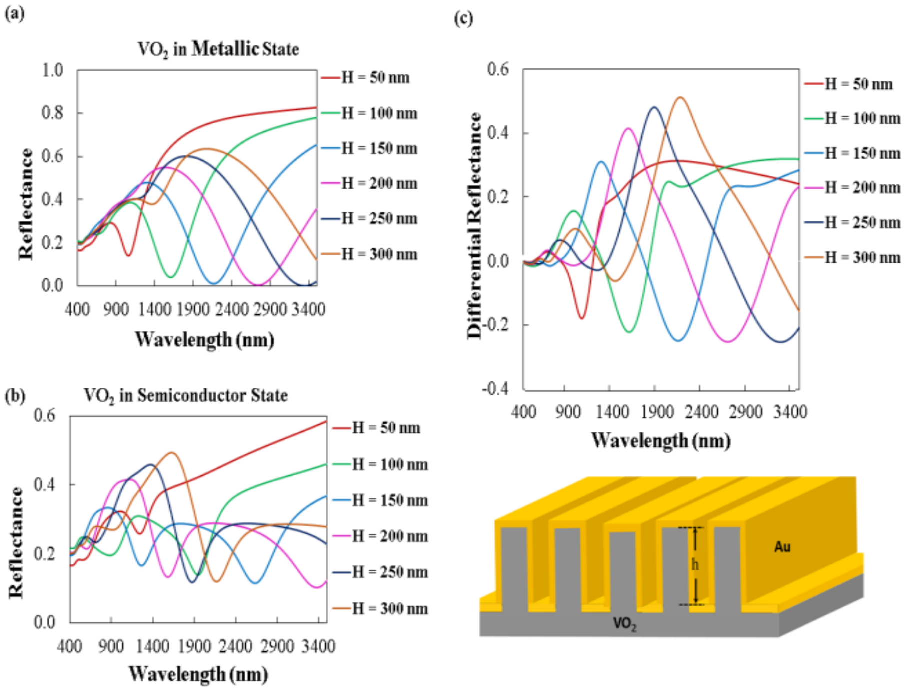

Figure 6 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (1D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (1D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (1D) nanograting. For all the above cases, t = 8, g = 10 and w = 100 nm were taken.

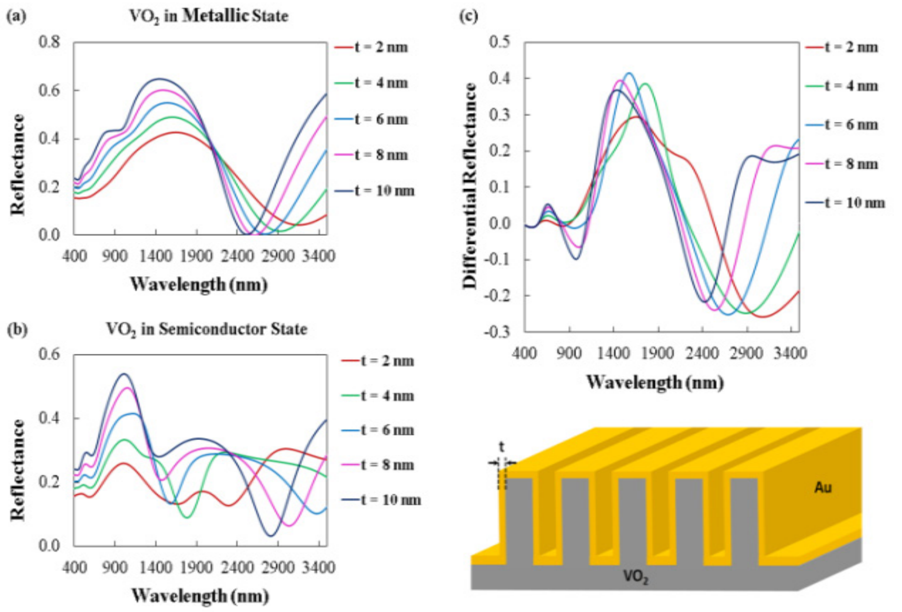

Figure 7 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (2D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (2D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (2D) nanograting. For all the above cases, g = 10, h = 200 and w = 100 nm were taken.

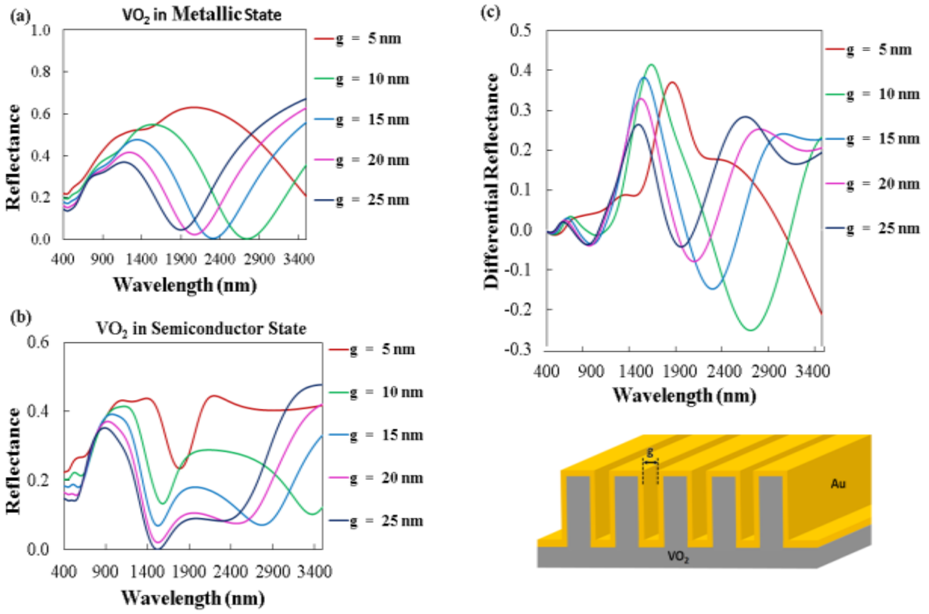

Figure 8 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (2D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (2D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (2D) nanograting. For all the above cases, t = 8, h = 200 and w = 100 nm were taken.

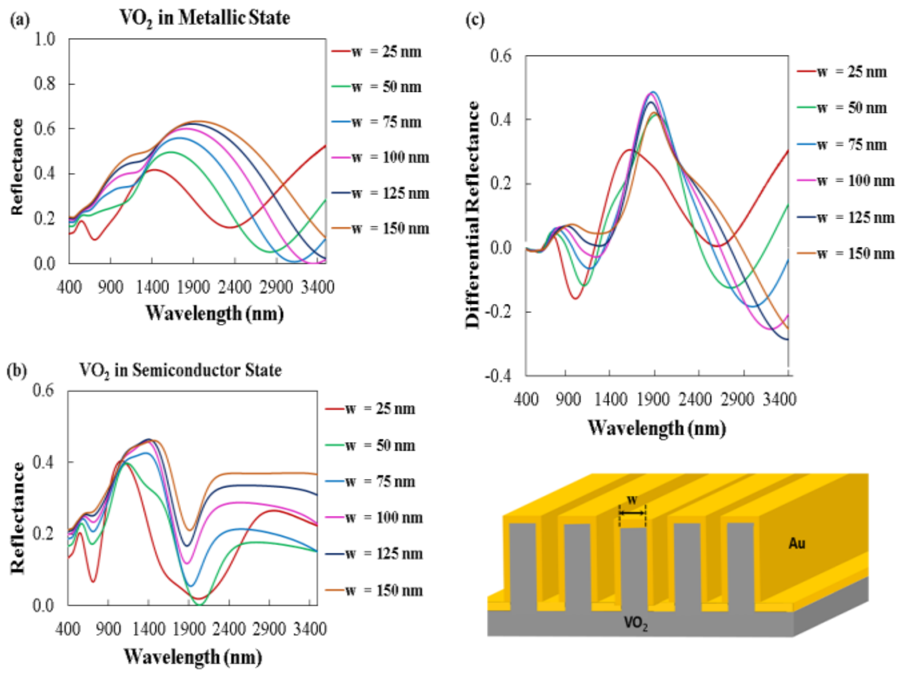

Figure 9 (a) reflectance versus wavelength curves for Au coated VO_2 (M) (2D) nanograting, (b) reflectance versus wavelength curves for Au coated VO_2 (S) (2D) nanograting and (c) differential reflectance versus wavelength curves for Au coated VO_2 (2D) nanograting. For all the above cases, t = 8, g = 10 and h = 200 nm were taken.

Conclusions

Au coated VO_2 plasmonic nanogratings - both 1D and 2D nanogratings - were proposed for optical switching over a wide spectral regime. VO_2 changes its state from the semiconductor state to the metallic state on application of heat, current, voltage, or optical radiation. This changes the refractive index of VO_2, which in turn modifies the optical properties of the proposed VO_2 nanogratings over-coated with Au. By varying the nanograting parameters like nanograting h, g between the nanogrooves, t of Au plating, and periodicity of the nanogratings, we can tune the wavelength of switching and magnitude of switchabilty for both the cases, i.e., 1D and 2D nanogratings. Hence, by employing the optimized 1D and 2D nanogratings described in this paper, we can achieve high switchabilty as well tunability of the switching wavalengths.

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