Supporting Information

Tailoring TiO_2/Al_2O_3 Heterolayers as Optical Filters for Visible Region

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Supporting Information contains the following content:

Table: S4 Design of 7 long wave pass edge filer in visible region reference wavelength 563 nm.

Table: S5 Design of 7 layers long wave pass edge filter infra-red region reference wavelength 810 nm.

Table: S6 Design of 7 long wave pass edge filter ultraviolet region reference wavelength 400 nm.

Fig. S1. Essential MacLeod is thin film design software. The fundamental purpose of this software is to integrate the tool which carries out design and analysis of thin film optical coating.

Fig.S2. (**a**) Transmission (%) versus wavelength (nm) spectra of 14 layers band pass filter Infra-red region. (**b**) Three-Dimensional (3D) view of spectra transmission (%) versus wavelength (nm).

Fig.S3. **(a)** Transmission (%) versus wavelength (nm) spectra of 17 layer band pass filter Visible region of spectrum. (**b**) Three-Dimensional 3D view of spectra Transmission (%) versus wavelength (nm). (**c**) Transmission (%) versus wavelength (nm) spectra of 20 layers

band pass. (**d**) Three-Dimensional (3D) view of spectra Transmission (%) versus wavelength (nm).

Fig. S4. (**a**) Simulated measured performance of Transmission (%) versus wavelength (nm) Seven layers TiO_2/Al_2O_3/glass longwave pass edge filter visible region. (**b**) Transmission (%) versus wavelength (nm) performance of seven layers TiO_2/ZrO_2/glass longwave pass edge filter in visible region. (**c**) Transmission (nm) versus wavelength (nm) performance of seven layers TiO_2/Al_2O_3/glass infra-red region. (**d**) Transmission (%) versus wavelength (nm) performance of seven layers TiO_2/Al_2O_3/glass longwave pass edge filter in ultraviolet region.

Fig.S5. (**a**) PVD Magnetron Sputtering (RF) system. (**b**) M-2000 Spectroscopic Ellipsometry system.

Fig.S6. (**a**) Transmission (%) versus wavelength (nm) of Al_2O_3 single layer. (**b**) Transmission (%) versus wavelength (nm) of TiO_2. (**c**) Reflection versus wavelength (nm) of Al_2O_3. (**d**) Reflection (%) versus wavelength (nm) of TiO_2 single layer.

Note S1. Detail Simulated Design optical filter using Essential McLeod software

***Essential Macleod software*:** Essential Macleod program contain all design and performance of optical material. It is useful for reflectance, transmittance and phase. But also, color, ultrafast, ellipsometery quantities from zero's up to third derivation as a function of wavelength.

For this software five main task

1. The calculation of the performance of the given design
2. The derivation of a coating design given a desired performance
3. The maintenance of optical constant data for the material
4. The analysis of the design for improving understanding
5. The incorporation of the design as a component of complete filter

14 layers band pass filter reference wavelength 850 nm: Transmission spectra of simulation of 14 layers of band pass optical filter are shown in. At wavelength 650 nm the transmission has minimum value of 76.37 %. After 650 nm the transmission increased as the wavelength increases and has maximum value 97.37 % at 681 nm. Beyond this wavelength transmission began to decrease and we get second minimum value 78.67% at 727.48 nm. After 727.48 nm transmission again began to decrease and we get second maximum 96.62% at 783.81nm. Maximum value of transmission obtained at 954.80 nm is 99.40 %. The resonance wavelength of the $[2TiO_2Al_2O_3]^4 2TiO_2$ film was 850 nm and each titania layer in the stack had a thickness quarter of quarter wavelength1/4(λ/4n), and alumina has a thickness of half of Quarter wavelength

1/2(λ/4n). Here, n represent the refractive index of TiO_2 and Al_2O_3 at the designed wavelength respectively. The total thickness of this design was 641.43 nm.

17 layers band pass filter reference wavelength 550 nm: optical filter consisting upon 17 layers was designed in visible region at reference wavelength of 510 nm, its transmission spectra of simulation at 400 nm the transmission has minimum value 26.95 %. After400 nm the transmission values increased abruptly, as the wavelength increases and has maximum value of 99.62 % at 416 nm. At 615 nm the transmission has again maximum value of 99.00 %. After this wavelength, transmission began to decrease as the wavelength increased and has minimum value of transmission of 7.8 % at at 445 nm. The resonance wavelength of the $[2TiO_2Al_2O_3]^4 2TiO_2$ film was 510 nm and each TiO_2 layer in the stack had a thickness of quarter wavelength1/4(λ/4n), and Al_2O_3 has a thickness of half of Quarter wavelength 1/2(λ/4n). Here, n represent the refractive index of TiO_2 and Al_2O_3 at the designed wavelength respectively. Each layer of TiO_2 and Al_2O_3 has thickness of 55.43 nm and 76.54 nm respectively. The total thickness of this design is 1047.93 nm.

***20 layers band pass filter reference wavelength 510 nm*:** optical filter consisting upon 20 layers was designed in visible region at reference wavelength of 510 nm, its transmission spectra of simulation at 400 nm the transmission has minimum value 22.53 %. After 400 nm the transmission value increased abruptly, as the wavelength increases and has maximum value of 99.73 % at 413 nm. At 621 nm the transmission has again maximum value of 99.22 %. After this wavelength, transmission began to decrease as the wavelength increased and has minimum value of transmission of 35.94% at 667 nm. The resonance wavelength of the $[2TiO_2Al_2O_3]^6 2TiO_2$ film was 510 nm and each TiO_2 layer in the stack had a thickness of quarter wavelength 1/4 (λ/4n), and Al_2O_3 has a thickness of Quarter wavelength 1/2 (λ/4n). Here, n represent the refractive index of TiO_2 and Al_2O_3 at the designed wavelength respectively. Each layer of TiO_2 and Al_2O_3 has thickness of 55.43 nm and 76.54 nm, respectively. The total thickness of this design is 1235.34 nm.

Longwave pass edge filter seven layers Reference Wavelength 563 nm: longwave pass edge filter design material used TiO_2 and Al_2O_3 reference wavelength 563 nm in visible region. When graph drawn between wavelength and transmission. Transmission is maximum infrared to visible region 100% and edge drop in 650nm and now transmission value become zero at 500 nm this is called longwave pass edge filter.

Seven layers TiO_2/ZrO_2 longwave pass edge filter reference wavelength 563 nm and total thickness 388.23 nm: longwave pass edge filter design material used TiO_2 and ZrO_2 reference wavelength 563 nm in visible region. When graph drawn between wavelength and transmission, transmission value shown maximum value infra-red to visible region in 590 nm transmission edge drop and 500 nm transmission value become minimum less than 45 % this is called longwave pass edge filter in visible region.

Seven layers longwave pass edge filter reference Wavelength 810 nm: longwave pass edge filter material used TiO_2 and Al_2O_3 reference wavelength 810 nm in infra-red region. 1000-2500 nm transmission value become maximum value grater then 90 %. In 950 nm transmission edge drop and now decreased in 900 nm become minimum value less than 30 % in 800 nm to 700 nm this is called longwave pass edge filter.

Seven layers longwave pass edge filter with reference wavelength 400 nm: longwave pass edge filter design material used TiO_2 and Al_2O_3 reference wavelength 320 nm ultraviolet region. In visible region transmission value maximum 100 % 450-700 nm and now transmission edge drop in 450 nm value tend to decreased become minimum value 350-400 nm less than 10% called longwave pass edge filter in ultraviolet (UV) region.

Note S2. Sample characterization spectroscopic ellipsometery measurement

Optical analysis: extinction coefficient and refractive index in optical characterization are important parameters. Both can be calculating following equation.

$$k = \frac{\alpha\lambda}{4\pi}$$

The real part and imaginary part of complex dielectric constant are function of wavelength (λ) calculated by following equations.

$$\epsilon_{1=}n^2 \_k^2$$

$$\epsilon_{2=}\ 2nk$$

Thickness is calculated using this formula given below

$$t = \frac{M\lambda_1\lambda_2}{2(n_1\lambda_2 - n_2\lambda_1)}$$

t is thickness of thin film, M=1for direct band gap material. Band gap of material can be calculated by

$$\alpha hv = A(hv - E_g)^{1/2}$$

Energy in photon hv, A proportionality constant and E_g is band gap of material.

Transmission was increase when wavelength increase in ultraviolet region when 300 nm transmission is abrupt change comes to increase in visible region change of transmission very slowly and tend to increase wavelength is 800 nm infrared region transmission comes to constant this value of transmission is maximum 90 % in this region. In literature Al_2O_3 thin film 90% optical transparent in visible region and near infra-red region (up to 2300 nm) our experiment value is also 90 % in visible region. Transmission data shows 90 % transmittance which film is deposited 1 hour by RF magnetron sputtering and average transmittance 85 %. The trend of thin film is same as our experiment result transmission graph shows 90 % transmittance value. Transmission of this sample is high =90 % so reflection is less. This result shows that thin film is highly transparent because reflection is very less. In visible region some reflection is show almost 20 % when infrared region reflection is less than 10 %. Because by in region transmission is much high 90 % almost. If transmission is higher than reflectance is lower because this trend is inverse one value is grater and other was smaller thin film is prepared by RF magnetron sputtering 1 hour. Where our experiment result of thin film deposition time 30 minute literature and our result much similar. Transmission is 90 % at wavelength approximately equal to 850 nm. All samples power is same 50 Watt and deposition time is different 30 minute, 60 minute and 90 minute. At 30 minute transmission is higher than at 60 minute and 90min.At 60 minute transmission is less than 90 % and 90 minute transmission is less than 60 %. In paper average transmission value in visible region is 77 % to 82 % our experiment value is also>80 %. Graph shows that reflection much lesser than the transmission. At 30 minute and 50 Watt reflection is less than the 60 minute and 90 minute. So we can say thin films are transparent. Transmission average value 75 % when the reflection was

15 % average value. Trend of reflection graph was change with wavelength and show small reflection.

Table S1: *Design of 14 layers band pass filter infra-red region reference wavelength 850 nm.*

Layer	***Material***	***Refractive Index***	***Extinction Coefficient***	***Optical thickness (FWOT)***	***Thickness (nm)***
1	TiO_2	1.59289	0.00000	0.625000000	33.35
2	TiO_2	1.59289	0.00000	0.625000000	33.35
3	Al_2O_3	1.38025	0.00000	0.125000000	76.98
4	TiO_2	1.59289	0.00000	0.625000000	33.35
5	TiO_2	1.59289	0.00000	0.625000000	33.35
6	Al_2O_3	1.38025	0.00000	0.125000000	76.98
7	TiO_2	1.59289	0.00000	0.625000000	33.35
8	TiO_2	1.59289	0.00000	0.625000000	33.35
9	Al_2O_3	1.38025	0.00000	0.125000000	76.98
10	TiO_2	1.59289	0.00000	0.625000000	33.35
11	TiO_2	1.59289	0.00000	0.625000000	33.35
12	Al_2O_3	1.38025	0.00000	0.125000000	76.98
13	TiO_2	1.59289	0.00000	0.625000000	33.35
14	TiO_2	1.59289	0.00000	0.625000000	33.35
Total Thickness					641.43

(nm)

Table S2: *Design of 17 layers Band pass filter visible region reference wavelength 550 nm.*

Layer	***Material***	***Refractive Index***	***Extinction Coefficient***	***Optical thickness (FWOT)***	***Thickness (nm)***
1	TiO_2	2.30000	0.00000	0.25000000	55.43
2	TiO_2	2.30000	0.00000	0.25000000	55.43
3	Al_2O_3	1.66574	0.00000	0.25000000	76.54
4	TiO_2	2.30000	0.00000	0.25000000	55.43
5	TiO_2	2.30000	0.00000	0.25000000	55.43
6	Al_2O_3	1.66574	0.00000	0.25000000	76.54
7	TiO_2	2.30000	0.00000	0.25000000	55.43
8	TiO_2	2.30000	0.00000	0.25000000	55.43
9	Al_2O_3	1.66574	0.00000	0.25000000	76.54
10	TiO_2	2.30000	0.00000	0.25000000	55.43
11	TiO_2	2.30000	0.00000	0.25000000	55.43
12	Al_2O_3	1.66574	0.00000	0.25000000	76.54
13	TiO_2	2.30000	0.00000	0.25000000	55.43
14	TiO_2	2.30000	0.00000	0.25000000	55.43
15	Al_2O_3	1.66574	0.00000	0.25000000	76.54
16	TiO_2	2.30000	0.00000	0.25000000	55.43

17	TiO_2	2.30000	0.00000	0.25000000	55.43
Total Thickness (nm)					1047.93

Table S3: *Design of 20 layers band pass filter visible region reference wavelength 510 nm.*

Layer	***Material***	***Refractive Index***	***Extinction Coefficient***	***Optical Thickness (FWOT)***	***Thickness (nm)***
1	TiO_2	2.30000	0.00000	0.25000000	55.43
2	TiO_2	2.30000	0.00000	0.25000000	55.43
3	Al_2O_3	1.66574	0.00000	0.25000000	76.54
4	TiO_2	2.30000	0.00000	0.25000000	55.43
5	TiO_2	2.30000	0.00000	0.25000000	55.43
6	Al_2O_3	1.66574	0.00000	0.25000000	76.54
7	TiO_2	2.30000	0.00000	0.25000000	55.43
8	TiO_2	2.30000	0.00000	0.25000000	55.43
9	Al_2O_3	1.66574	0.00000	0.25000000	76.54
10	TiO_2	2.30000	0.00000	0.25000000	55.43
11	TiO_2	2.30000	0.00000	0.25000000	55.43
12	Al_2O_3	1.66574	0.00000	0.25000000	76.54
13	TiO_2	2.30000	0.00000	0.25000000	55.43
14	TiO_2	2.30000	0.00000	0.25000000	55.43
15	Al_2O_3	1.66574	0.00000	0.25000000	76.54
16	TiO_2	2.30000	0.00000	0.25000000	55.43
17	TiO_2	2.30000	0.00000	0.25000000	55.43
18	Al_2O_3	1.66574	0.00000	0.25000000	76.54

19	TiO_2	2.30000	0.00000	0.25000000	55.43
20	TiO_2	2.30000	0.00000	0.25000000	55.43
Total Thickness (nm)					1235.34

Table S4: *Design of 7 longwave pass edge filer visible region reference wavelength 563 nm.*

Layers	***Material***	***Refractive Index***	***Extinction Coefficient***	***Optical Thickness (FWOT)***	***Thickness (nm)***
1	TiO_2	2.31064	0.00011	0.12500000	30.46
2	Al_2O_3	1.66212	0.00000	0.25000000	84.68
3	TiO_2	2.31064	0.00011	0.25000000	60.91
4	Al_2O_3	1.66212	0.00000	0.25000000	84.68
5	TiO_2	2.31064	0.00011	0.25000000	60.91
6	Al_2O_3	1.66212	0.00000	0.25000000	84.68
7	TiO_2	2.31064	0.00011	0.12500000	30.46
Total Thickness (nm)					436.78

Table S5: *Design of 7 layers longwave pass edge filter reference wavelength 810 nm.*

Layer	***Material***	***Refractive Index***	***Extinction Coefficient***	***Thickness (FWOT)***	***Thickness (nm)***
1	TiO_2	2.25000	0.00000	0.12500000	45.00
2	Al_2O_3	1.65296	0.00000	0.25000000	122.51
3	TiO_2	2.25000	0.00000	0.25000000	90.00
4	Al_2O_3	1.65296	0.00000	0.25000000	122.51
5	TiO_2	2.25000	0.00000	0.25000000	90.00
6	Al_2O_3	1.65296	0.00000	0.25000000	122.51
7	TiO_2	2.25000	0.00000	0.12500000	45.00
Total Thickness (nm)					637.52

Table S6: *Design of 7 longwave pass edge filter with reference wavelength 400 nm.*

Layer	Material	refractive Index	Extinction Coefficient	Thickness (FWOT)	Thickness (nm
1	TiO_2	2.54627	0.00253	0.12500000	19.64
2	Al_2O_3	1.67800	0.00000	0.25000000	59.59
3	TiO_2	2.54627	0.00253	0.25000000	39.27
4	Al_2O_3	1.67800	0.00000	0.25000000	59.59
5	TiO_2	2.54627	0.00253	0.25000000	39.27
6	Al_2O_3	1.67800	0.00000	0.25000000	59.59
7	TiO_2	2.54627	0.00253	0.12500000	19.64
Total Thickness (nm)					296.60

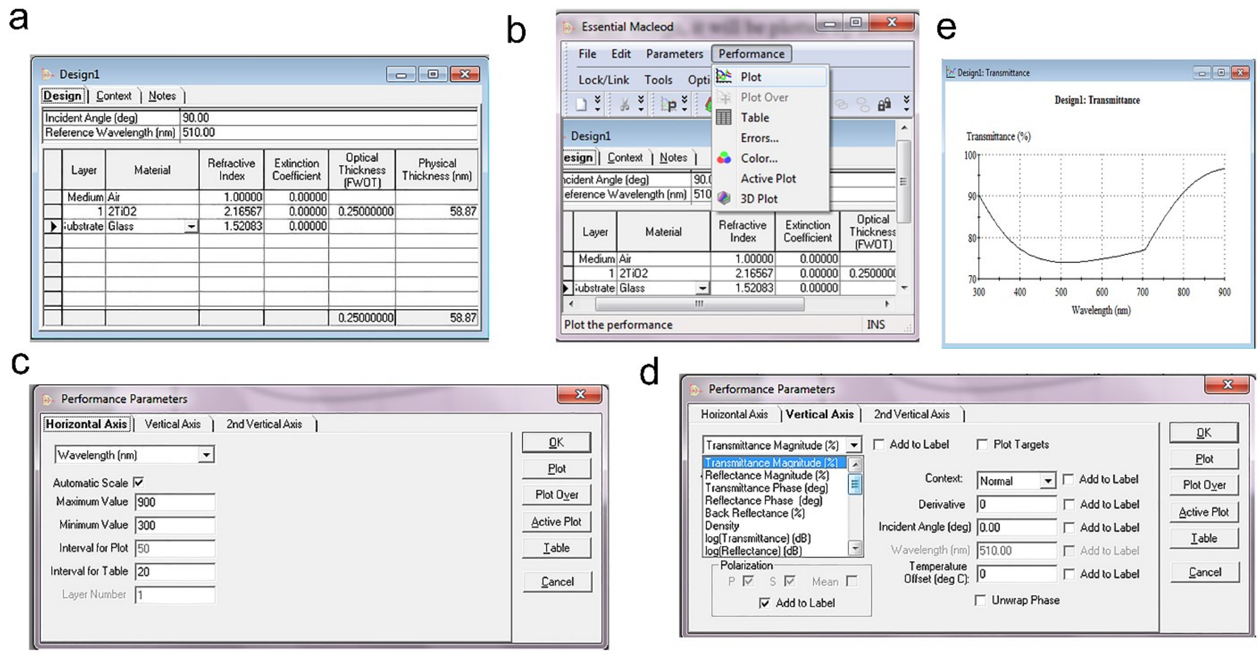

Figure S1: (**a**) In the design reference wavelength value is 510nm. All wavelength values will be in nm. In the design table the incident medium will be air. The substrate will be on the lower side of the table all layers will be deposited on it. The layers are numbered from incident to substrate rather than from substrate to incident. The design consisted upon "six" column. These columns are labeled as "Layers", "Material", "Refractive index", "Extinction coefficient", Optical thickness and "Physical Thickness" respectively. The values of extinction coefficient, physical thickness and optical thickness will be changed with reference wavelength. Layer column contains the layer number, incident medium, and substrate. Last three columns contain the information about the materials. The fourth column contains optical thickness which is determined by the relation nd/λ_o, here n is refractive index, d is physical thickness and λ_o represents the reference wavelength. **(b)** To see the performance of this design, it will be plotted by clicking on plot form the option of the performance. The performance tool contains seven sub icons such as plot, plot over, table, errors, color, active plot, 3D. By clicking on the plot a new window appears which has title as "Design1 Transmittance". (**c**) A new window "performance parameter" will be open which contain three sub-menu named as horizontal axis, vertical axis and second vertical axis. At horizontal sub-menu, we can set the minimum wavelength, maximum wavelength, plot intervals, interval for table. (**d**) Vertical axis also contains the maximum value, minimum value and interval for plot. It also contains polarization icon, p-polarization, s-polarization and mean polarization can be set by this icon. we can set the parameters of vertical axis to find out the transmittance magnitude (%), Reflectance magnitude (%), transmittance phase (deg), reflectance phase (deg), Back reflectance (%), Density, log (transmission) (dB), log (Reflectance) (dB), absorbance(%), Reflectance(etc. of the given design. Second vertical axis also contains same icons. (**e**) Design1 Transmittance window will show the transmittance of the design against wavelength ranges from 300 to 900 nm.

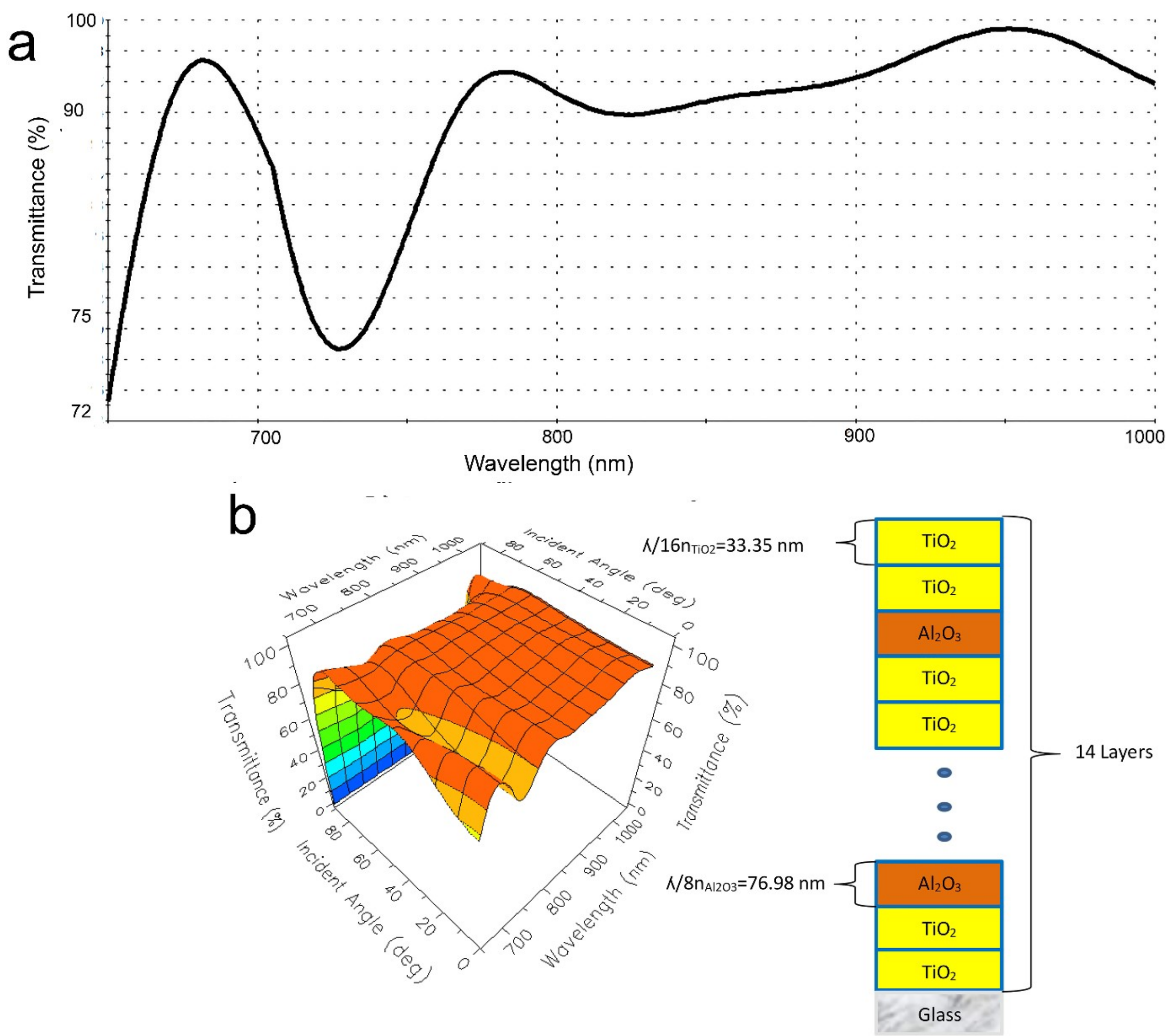

Figure S2: (**a**) Transmission (%) versus wavelength (nm) spectra of 14 layers band pass filter infra-red region with reference wavelength 850 nm. (**b**) Three-dimensional (3D) view of spectra transmission (%) versus wavelength (nm) with incident angle (deg) and physical design of 14 layers band pass filter.

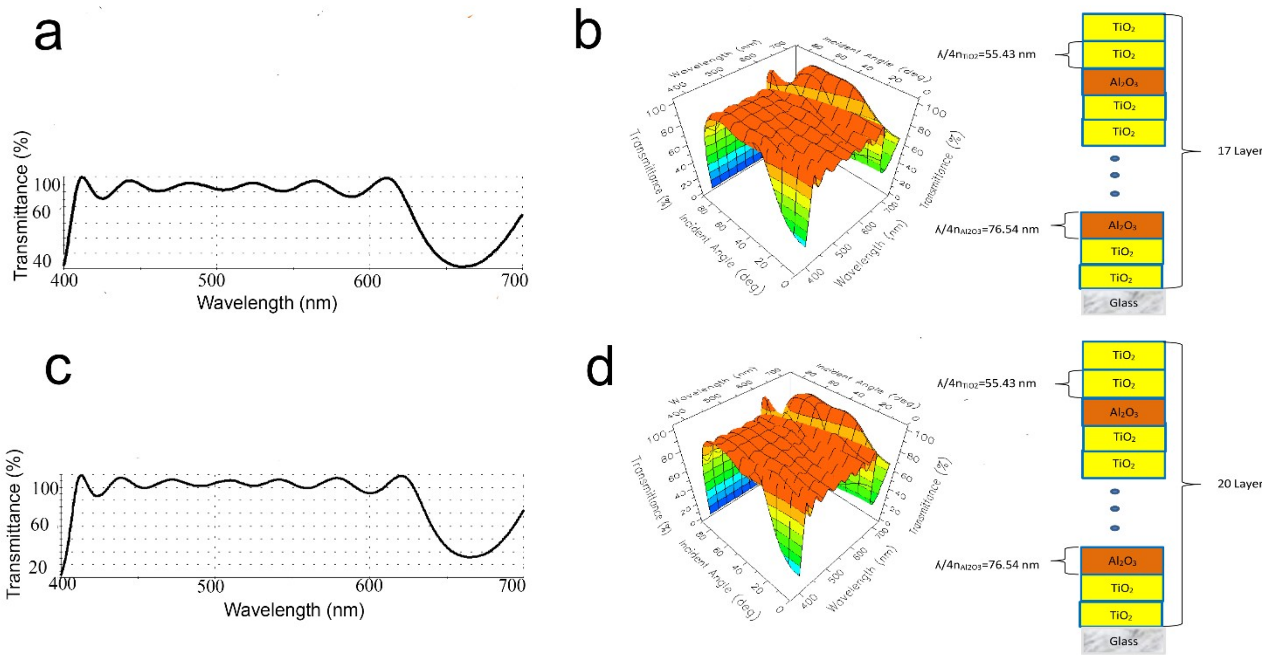

Figure S3: (**a**) Transmission (%) versus wavelength (nm) spectra of 17 layer band pass filter in visible region of spectrum. (**b**) Three-dimensional 3D view of spectra Transmission (%) versus wavelength (nm) with incident angle (drg) spectra and physical design of 17 layers band pass filter. (**c**) Transmission (%) versus wavelength (nm) spectra of 20 layers band pass filter in visible region of spectrum. (**d**) Three-dimensional (3D) view of spectra Transmission (%) versus wavelength (nm) with incident angle (deg) and physical design of 20 layers band pass filter.

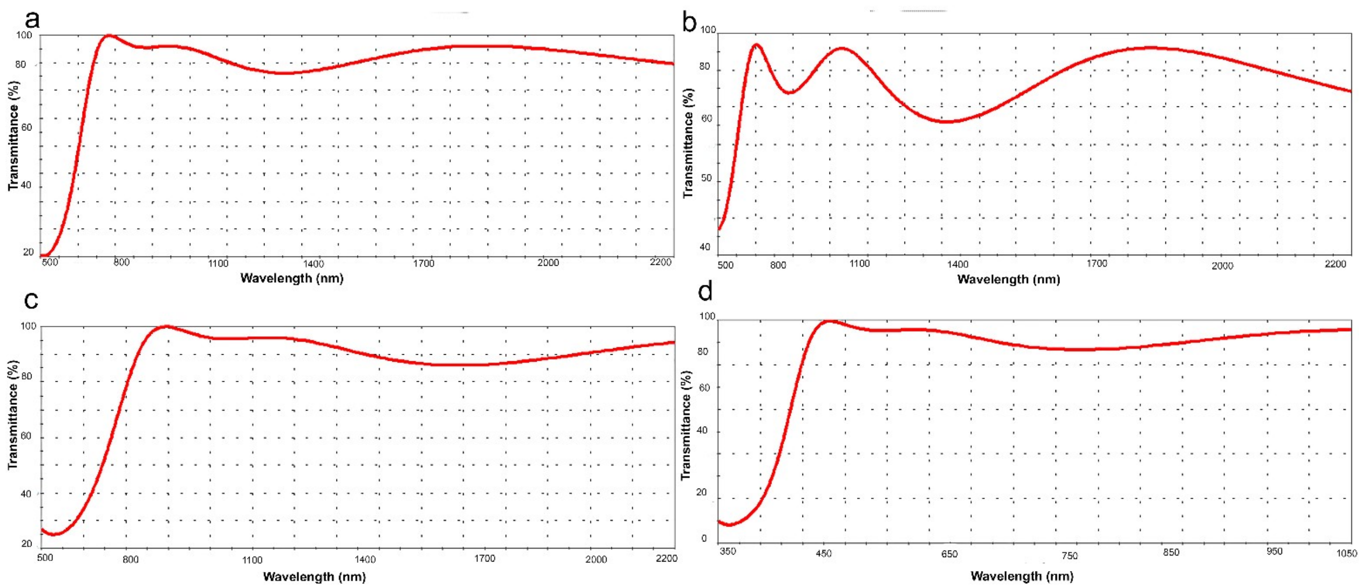

Figure S4: (**a**) simulated measured performance of Transmission (%) versus Wavelength (nm) seven layers TiO_2/Al_2O_3/glass longwave pass edge filter in visible region with the reference wavelength 563 nm. (**b**) Transmission (%) versus wavelength (nm) performance of seven layers TiO_2/ZrO_2/glass longwave pass edge filter in visible region with reference wavelength 563 nm. (**c**) Transmission (nm) versus wavelength (nm) performance of seven layers TiO_2/Al_2O_3/glass longwave pass edge filter in infra-red region with reference wavelength 810 nm. (**d**) Transmission (%) versus wavelength (nm) performance of seven layers TiO_2/Al_2O_3/glass longwave pass edge filter in ultraviolet region with the reference wavelength 400 nm.

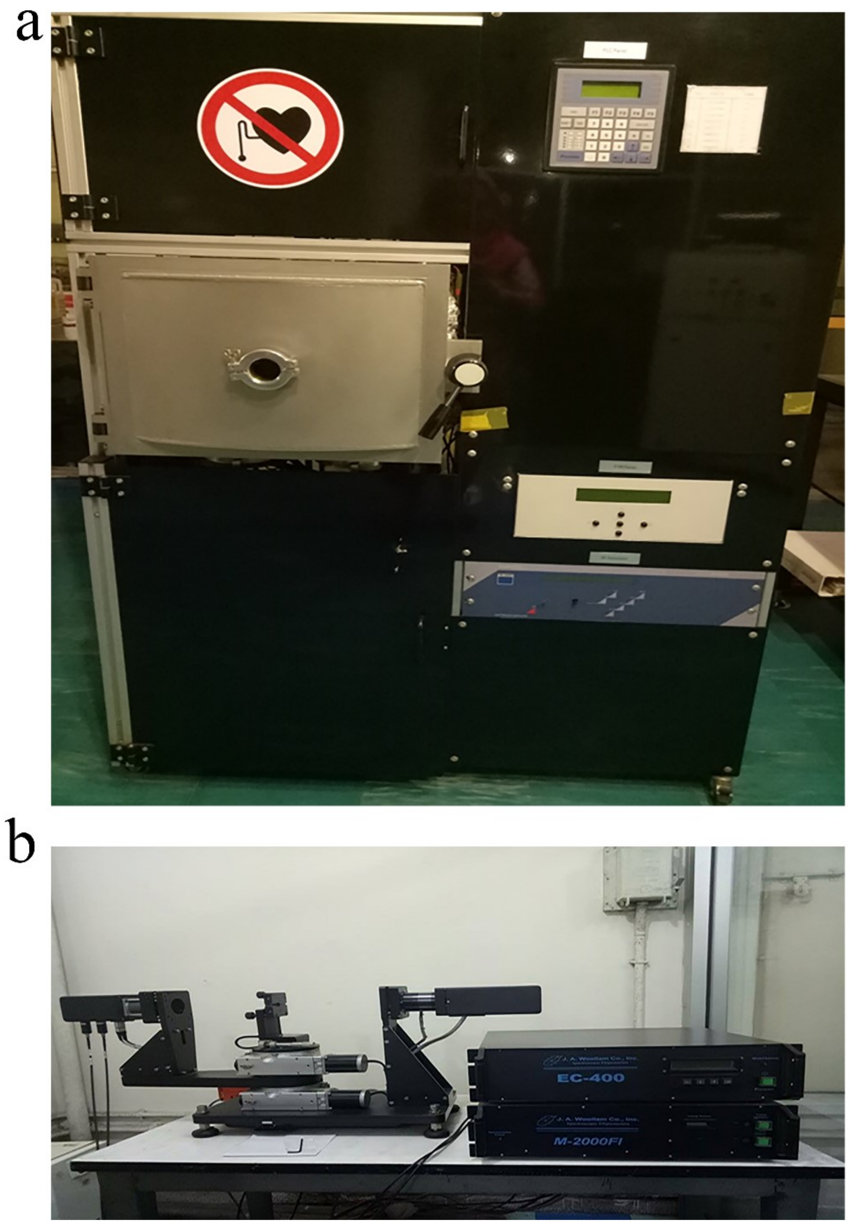

Figure S5: (**a**) PVD Magnetron Sputtering (RF) system for the deposition of single and hetero layers with changing the parameter like time but power and gas flow fixed. (**b**) M-2000 Spectroscopic Ellipsometery system for optical characterization refractive index, extinction coefficient, transmission and reflection in visible region of spectrum.

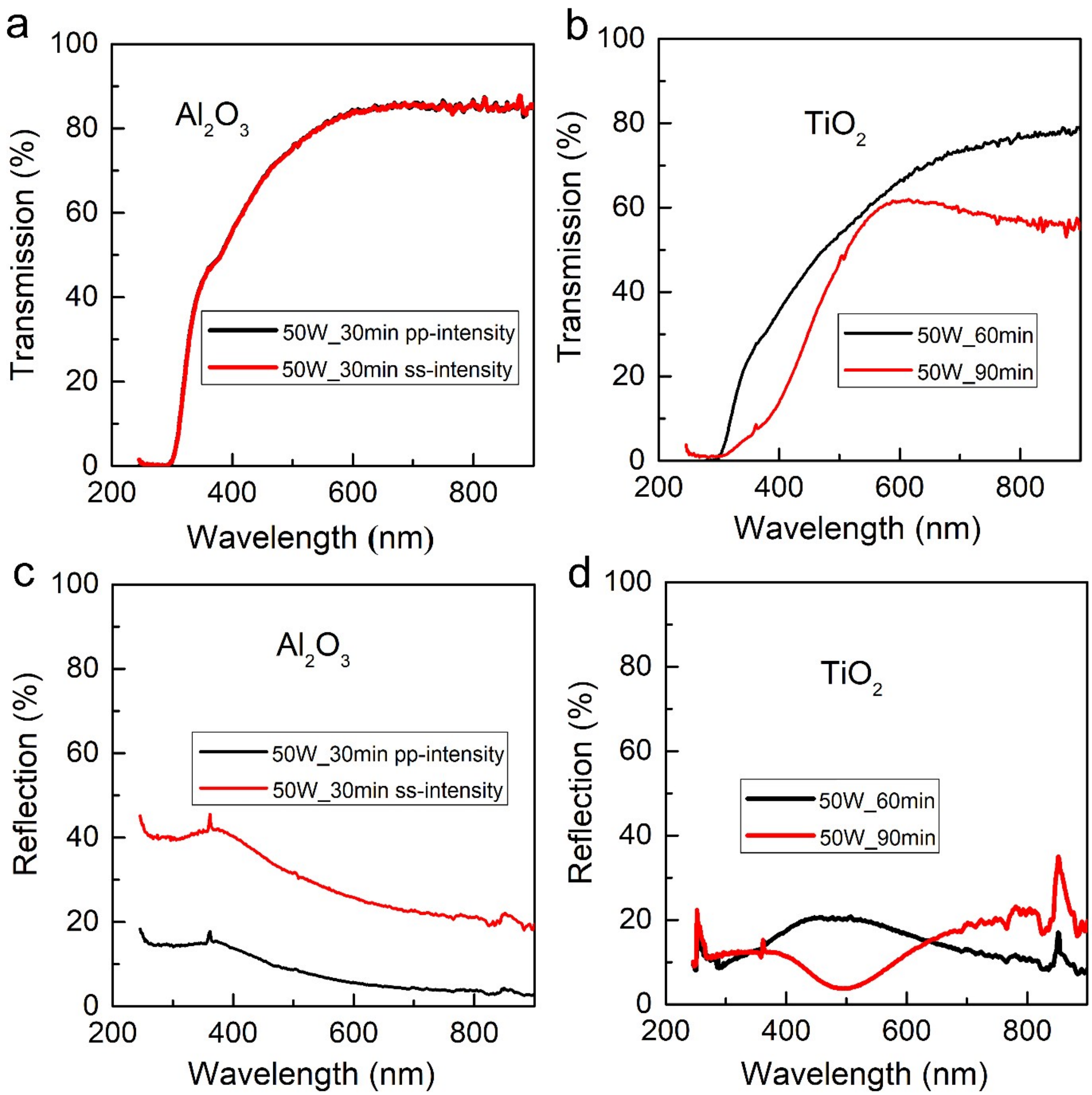

Figure S6: (**a**) Transmission (%) versus wavelength (nm) of Al_2O_3 single layer (30 minute and 50 Watt). (**b**) Transmission (%) versus wavelength (nm) TiO2 (60 minute, 90 minute and 50 Watt). (**c**) Reflection (%) versus wavelength (nm) Al_2O_3 (30 minute, 50 Watt). (**d**) Reflection (%) versus wavelength (nm) of TiO_2 single layer (60 minute, 90 minute and 50 Watt).