Electronic Supplementary Material (ESI) for Nanoscale.

A Voltage-Controlled Silver Nanograting Device for Dynamic Modulation of Transmitted Light Based on Surface Plasmon Polariton Effect

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1. The general theory of the VCP filter.

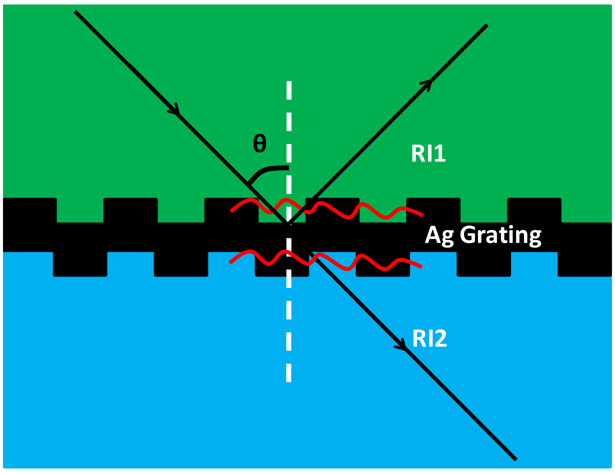

Figure S1. The physical model of the VCP filter. The VCP filter was simplified as a trilayer structure, containing a dielectric layer (RI1), LC layer (RI2) and the silver nanograting.

The VCP filter can be regarded as a three-layer structure composed of an Ag grating (the grating constant: a, thickness: d, dielectric function: ε_m), and two dielectric layers (refraction indexes: n_1 and n_{lc}, dielectric functions: ε_1 and ε_{lc}). As shown in figure S1, the model is illuminated by the incident light with the propagation vector of k_0. In the interface between RI1 and the Ag grating, the incident light is diffracted by the grooves of the grating. The propagation vector k_x in the interface can be expressed as

$$k_x = k_0 \sin\theta + m\frac{2\pi}{a} \tag{1}$$

where m is an integer. The SPP propagation vector bonding on the interface is

$$k_1 = \frac{\omega}{c}\sqrt{\frac{n_1^2\varepsilon_m}{n_1^2+\varepsilon_m}} \tag{2}$$

where k_1 is the propagation vector of the SPPs bonding on the interface between RI1 and Ag nanograting, c is the light speed in vacuum, and ω is the circular frequency. If the thickness of the Ag grating is infinite, the SPPs is excited when the equation (1) and equation (2) equaling known as 'vector matching'. However, the Ag grating in the VCP filter is 70nm. And a part of incident light penetrates the Ag grating to the interface between RI2 and Ag nanograting. The SPPs bonding on this interface can be excited when the vector matching occurs. The propagation vector of the incident light in this interface is

$$k_2 = \frac{\omega}{c}\sqrt{\frac{n_{lc}^2\varepsilon_m}{n_{lc}^2+\varepsilon_m}} \tag{3}$$

where k_2 is the propagation vector of the SPPs bonding on the interface between RI2 and Ag grating.

Considering the finite thickness of the metal layer, k_1 and k_2 are little different from equation (2) and (3). For the condition of $k_1 = k_2$, Reather[1] has given us the vector matching:

$$\varepsilon_m k_{z2} + n_{lc}^2 k_{zm} tanh\frac{k_{zm}d}{2i} = 0 \tag{4}$$

and

$$\varepsilon_m k_{z2} + n_{lc}^2 k_{zm} ctgh \frac{k_{zm} d}{2i} = 0 \quad (5)$$

the k_{z2} is the propagation vector in RI2 layer normal to the interface of Ag grating, and k_{zm} is the propagation vector in the Ag grating layer normal to the interface of Ag grating. The equation (4) and (5) correspond to the anti-symmetrical and symmetrical modes of the SPPs bonding on the interfaces of the Ag grating. We know, k_1 and k_2 should be expressed into a function of the thickness d and the two dielectric layer's RIs n_1 and n_{lc} as below,

$$k_1 = \frac{\omega}{c}\sqrt{\frac{n_1^2 \varepsilon_m}{n_1^2 + \varepsilon_m}} + \Delta k_1 \quad (6)$$

$$k_2 = \frac{\omega}{c}\sqrt{\frac{n_{lc}^2 \varepsilon_m}{n_{lc}^2 + \varepsilon_m}} + \Delta k_2 \quad (7)$$

the Δk_1 and Δk_2 are the function of d and ε_2 and ε_1,

$$\Delta k_1 \propto f(d) f(n_{lc}) \quad (8)$$

$$\Delta k_2 \propto f(d) f(n_1) \quad (9)$$

The expression of $f(d)$, $f(n_{lc})$ and $f(n_1)$ are very complex, so experiments and simulations with different thicknesses of Ag grating and different dielectric functions of the two dielectric layers are implemented. The experiment and simulation results reveal the relationships between the SPP wavelength and the thickness of Ag grating or the RIs of the dielectric layers. According to the RI-dependent reflection and transmission spectra, the transmission can be modulated via the RI of the dielectric layer. This results support the working principle of the VCP filter.

2. The thickness optimization of the Ag grating sandwiched by photoresist layers in experiment.

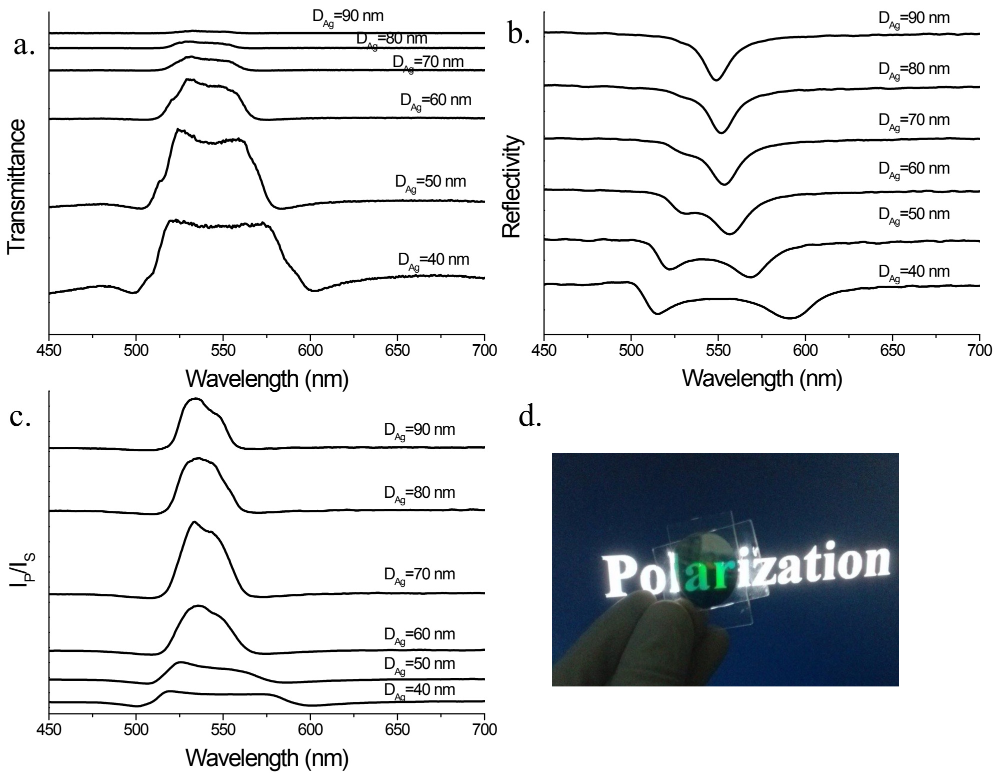

Figure S2 (a) The transmission spectra of the Ag grating with different thicknesses sandwiched by the photoresist layers on each side. (b) The reflection spectra of the Ag grating with different thicknesses. (c) The SPP bands of the Ag grating with different thicknesses sandwiched by photoresist on both sides. (d) A photo shows the filtering effect of the Ag grating sandwiched by photoresist layers in front of a display.

In order to obtain the best performance of the VCP filter, the thickness of the Ag grating is investigated with a photoresist layer (RI=1.53, K-302, Kafuter, China) attaching on the two sides of the Ag grating. As shown in Figure S2a and b, there are two strong SPP bands clearly in the transmission and reflection spectra, which are derived from the LRSPPs according to the FDTD simulation (Figure 1c and d in the main text). From the transmission spectra in Figure S2a, the band width becomes narrow and the intensity becomes weak with the thickness of the Ag grating increasing. We believe there are two effects dominating the transmission bands, the part-transmission/reflection effect and the SPPs. However, only the SPP effect is sensitive to the RI of the adjoined dielectric layer, which dominates the dynamic property of the VCP filter. In order to make the SPP effect clear, the transmission spectra of the TE incident light (which cannot excite the SPPs, and the transmission spectra only contain the part-transmission and –reflection effect) are recorded as the reference spectra. The SPP effects of the different thickness are obtained with the equation below

$$I_{spp} = I_{trans}/I_{TE} \qquad (10)$$

I_{spp} corresponds to the signal of the SPP effect and I_{trans} is the transmittance intensity, I_{TE} is the intensity of the transmittance when TE incident light is used. The SPP spectra of the Ag grating with different thicknesses sandwiched by photoresist on both sides are shown in Figure S2c. Below 70 nm, the SPP band width becomes narrow and the intensity goes strong with the thickness increasing. However, when the thickness reaches 70 nm, the width of the SPP band changes little. And the 70 nm Ag grating supports the strongest SPP effect as shown in Figure S2c. With a 70 nm-thickness Ag grating attached on both sides of the photoresist, figure S2d shows the color filtering effect. Part of the white words “polarization” in a LC display was filtered to green words, indicating its good light filtering ability.

3. RI Sensitivity.

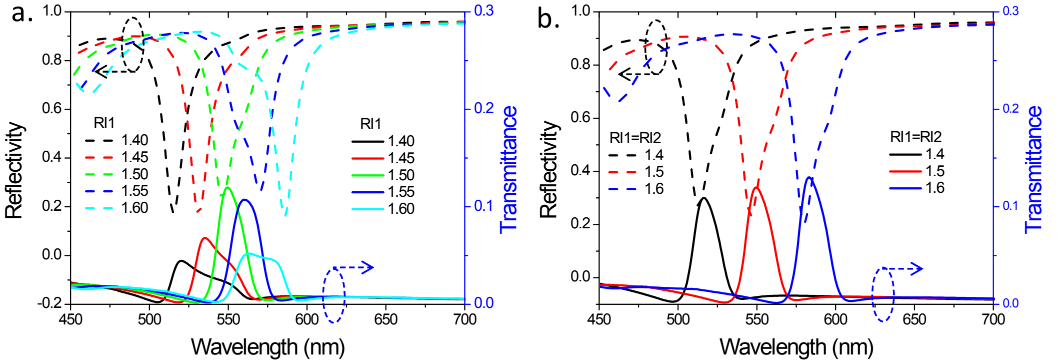

Figure S3.(a) The simulated SPP bands in different dielectric conditions. (b) The SPP bands shift to the long wavelength region when the RIs of both dielectric layers of light incident and SPP outgoing increase simultaneously.

In Figure S3a, SPP bands depending on the RIs of the dielectric layers are investigated. With a 320 nm period and a 70 nm thickness of the grating adopted, the SPP bands are red-shift along with the RI increasing as shown in Figure S3a. When RI1 changes from 1.4 to 1.6, the SPP band bonding on the light-incidence side of the Ag grating shifts to long wavelength region. In contrast, the SPPs bonding on the Ag grating in the light outgoing side has almost no change. When the RIs of the RI1 and RI2 layers are equal each other, the transmission band shows the strongest intensity, which is similar to the results shown in Figure 1e and f in main text. When the RIs of the RI1 and RI2 layers increase simultaneously shown in Figure S3b, SPP bands have a red-shift. This RI-sensitive property is utilized for the design of a VCP filter.

4. Image system.

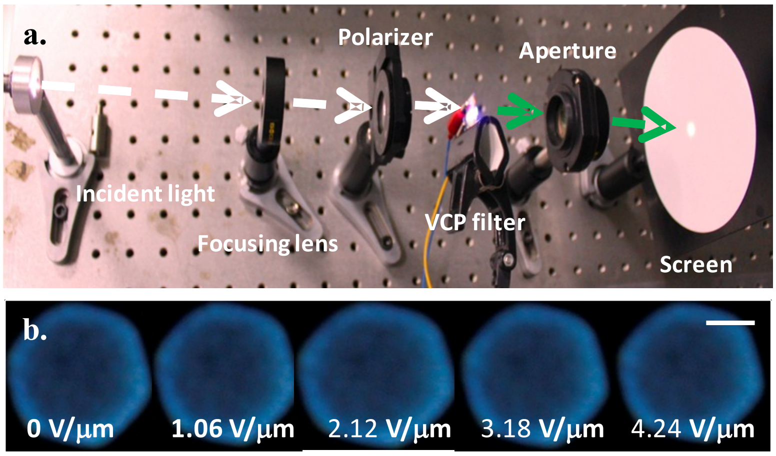

Figure S4.(a) The detection system for the picture of the VCP filter. A white light incident was coupled by a fiber coupler. The focusing lens makes the incident light into a parallel beam. Then the polarizer tunes the polarization direction of the parallel beam vertical to the direction of the Ag grating's graves. The white light is filtered into green and strikes on the screen in the right through an aperture. (b) Images of white light in TE polarization with different voltages applied on the LC layer.

5. Detection systems for transmission and reflection spectra.

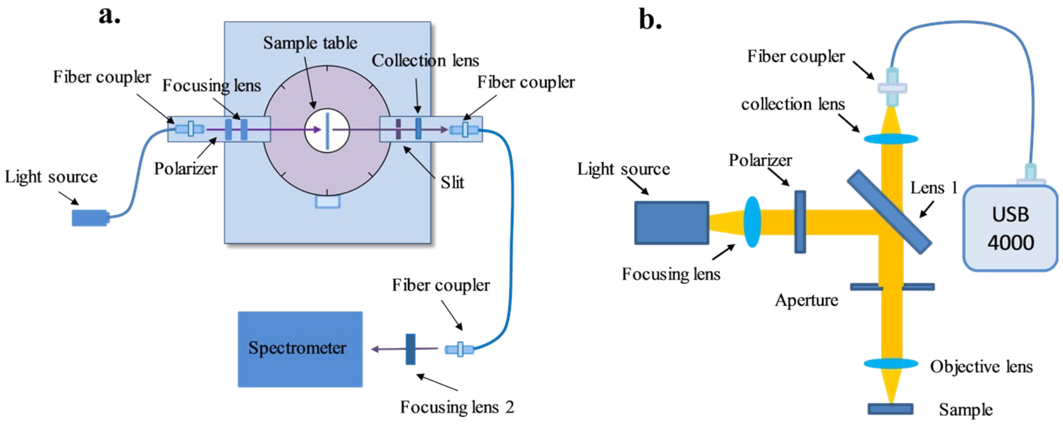

Figure S5.(a) The detection system of transmission spectra. (b) The detection system for reflection spectra.

The transmission spectra of the plasmonic filter were detected on the detection system in Figure S5a. The detection system is composed of a goniometer, a light source (a bromine tungsten lamp for recording transmission spectra) and a spectrometer with an intensifier charge-coupled device (ICCD, Princeton Instruments). The incident light (the white light from the bromine tungsten lamp) was first coupled into an optical fiber and then the light was tuned to parallel light through a fiber coupler. The focusing lens 1 (NA=0.05) and the fiber coupler are mounted on one arm of the goniometer. The parallel light passes through a TM polarizer (the polarization direction vertical to the strips of the Ag grating) and is focused to the plasmonic filter (supported by a sample stage) through the focusing lens 1. An adjustable slit was used for adjusting the collection angle and a collection lens (NA=0.03) was fixed on the other arm of the goniometer. Then the transmission signal was coupled into an optical fiber *via* a fiber coupler and decoupled out via another fiber coupler. Finally, the transmission signal was focused on the slit of the detection spectrometer (Princeton

Instruments) through focusing lens 2.

The reflection spectra were obtained in the system shown in Figure S5b. The system was refitted based on a commercial dark field microscope (Olympus). The primary eyepiece on the dark field microscope has been removed and replaced by an optical fiber to record the scattering spectra of samples via a fiber spectrometer (USB4000, Ocean Optics). The white light from a bromine tungsten lamp was converted into a parallel light by a focusing lens. It was converted into a polarized light through the polarizer and reflected to the VCP filter *via* lens 1 (a semi-transparent mirror). An aperture was used to tune the light beam and an objective lens (×5, Olympus) focused the parallel light to the surface of the VCP filter.The reflection light was collected by a collection lens (NA = 0.2) and coupled into a optical fiber. A fiber spectrometer (USB 4000, Ocean Optics) was used to record the reflection spectra.

6. Detection systems for the response time of VCP filter.

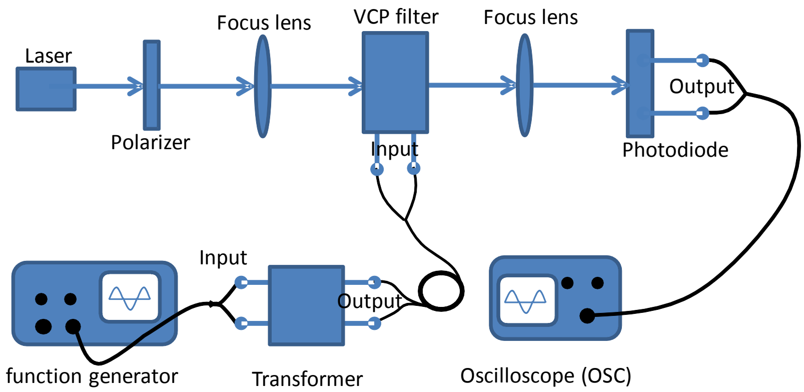

Figure S6. The detection system used to confirm the response time of the plasmonic filter.

REFERENCES

[1] H. Raether, *Surface plasmons on smooth and rough surfaces and on gratings* (Springer-Verlag, Berlin, New York, USA, 1988),pp. 91-116.