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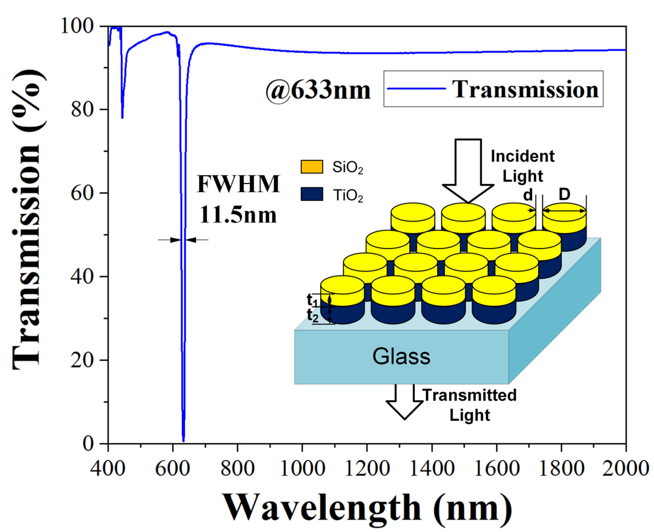

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All-Dielectric Metasurface for Highly Tunable, Narrowband Notch Filtering

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Abstract: A novel scheme of an all-dielectric metasurface with double-layer patch array is proposed to achieve the highly tunable, narrowband notch filtering across visible and near-infrared range. The all-dielectric metasurface presents efficient blocking (transmittance 0.01–0.0001) at targeted wavelength and high (>93%) transmission across the visible and near-infrared light range outside the targeted wavelength band. The bandwidth of the notch filter could be greatly compressed with this all-dielectric metasurface, compared with those typical interference notch filters for distinctive wavelengths. The effect of the geometrical parameters on the spectral filtering of this metasurface is studied to provide a distinct relationship to design the desired narrowband notch filter conveniently. And the antireflection effect of the top silicon dioxide layer is verified with similar bandwidth, lower transmission at notch filtering wavelength and higher transmission at other wavelengths. In addition, the optical Fano resonance excited by the all-dielectric metasurface is responsible for the spectral filtering feature including the deep blocking feature at the specific wavelength and high transmission at other wavelengths.

Index Terms: Notch filter, metasurface, narrowband.

1. Introduction

Notch filter [1], as a common optical component, selectively rejects a certain wavelength while transmitting all other wavelengths, which is widely used in fields of optical communication [2], [3], spectroscopy [4], laser-protection and so forth. Among the life science research and technology, spectroscopy, especially fluorescence spectroscopy, always places the notch filter in the setup to block the light from the pumped laser so as to better assess the characteristics of molecules through the isolation of specific wavelengths with good signal-to-noise ratios [5]. The traditional all-dielectric notch filter performs well by optical interference effect with the rugate film stacks. The thin film notch filter with tens even hundreds of layers can present large optical density (OD) within the desired wavelength region, i. e. low transmittance through this stack across this wavelength band while high transmission (>85%) is realized for the wavelength outside [1], [6]. The typical bandwidths of the interference notch filters are 17∼27 nm@532 nm, 20∼32 nm@633 nm, 34∼41 nm@808 nm, 44∼53 nm @1064 nm [7]–[9]. Hence, there is room to improve these notch filters including the

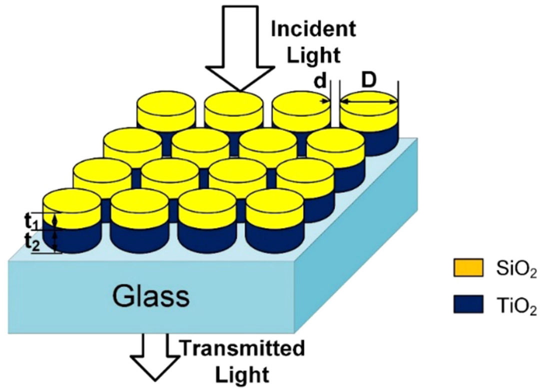

Fig. 1. Geometry of the proposed all-dielectric metasurface for highly tunable, narrowband notch filtering.

narrower bandwidth and simpler structure. However, little improvement for the notch filters have been carried out in recent decades.

Here, we propose an all-dielectric metasurface with double-layer patch array to achieve the highly tunable, narrowband notch filtering for visible (VIS) and near-infrared (NIR) range. The proposed all-dielectric metasurface is able to achieve deep blocking at specific wavelength while allowing other light passing with high transmission. With the all-dielectric metasurface, the bandwidth can be greatly compressed to half of the typical interference notch filter for distinctive wavelengths. We also analyzed the effect of the geometrical parameters on the transmission/filtering properties and provided a distinct relationship to design the desired narrowband notch filter conveniently. And the antireflection effect of the top silicon dioxide layer is demonstrated with the reduced dip transmission for the desired wavelength and increased transmission for other wavelengths. Through the analysis of the electric field of the structure, the physical origin of the phenomenon is verified that the Fano resonance excited within the structure leads to the narrowband notch filtering of this all-dielectric metasurface.

2. Structure and Design

The proposed all-dielectric metasurface is composed of double-layer dielectric patch array with the top layer using low refractive index and the bottom layer of high refractive index, shown in Fig. 1. In this paper, silicon dioxide (SiO_2) is selected as the patch material of the top layer while the titanium dioxide (TiO_2) is chosen as the bottom layer for its relatively high refractive index and good stability. The diameter of circle patch is denoted by **D**, the interval between the patches is denoted by **d** and the period of the structure is denoted by p while the thicknesses of the top SiO_2 layer and the bottom TiO_2 layer are represented by $\mathbf{t}_1$ and $\mathbf{t}_2$, respectively. A simple geometric relationship $\mathbf{p} = \mathbf{D}+\mathbf{d}$ could be obtained. The refractive index of SiO_2 and TiO_2 are set $n_{SiO2} = 1.5$ and $n_{TiO2} = 2.35$, respectively. In our work, the incident light illuminates the structure from the metasurface side and transmitted through the substrate, shown in Fig. 1. The finite-difference-time-domain (FDTD) method [10] is used for the transmission calculation and the electric field profile simulation while the particle swarm optimization (PSO) method [11] is applied for the structure design considering the center wavelength, narrow bandwidth, deep blocking efficiency, high transmission for transmission band. The PSO method is adopted in the optimization because of its advantage of fast convergence speed and less dependence on the initial parameters, which is demonstrated in our previous works [12]–[14].

TABLE 1
The Optimal Structural Parameters of the All-Dielectric Metasurfaces

Wavelength	t_1	t_2	D	d
532n m	60 nm	105 nm	290 nm	55 nm
633n m	75 nm	125 nm	350 nm	60 nm
808n m	90 nm	160 nm	445 nm	80 nm
1064 nm	165 nm	210 nm	595 nm	90 nm

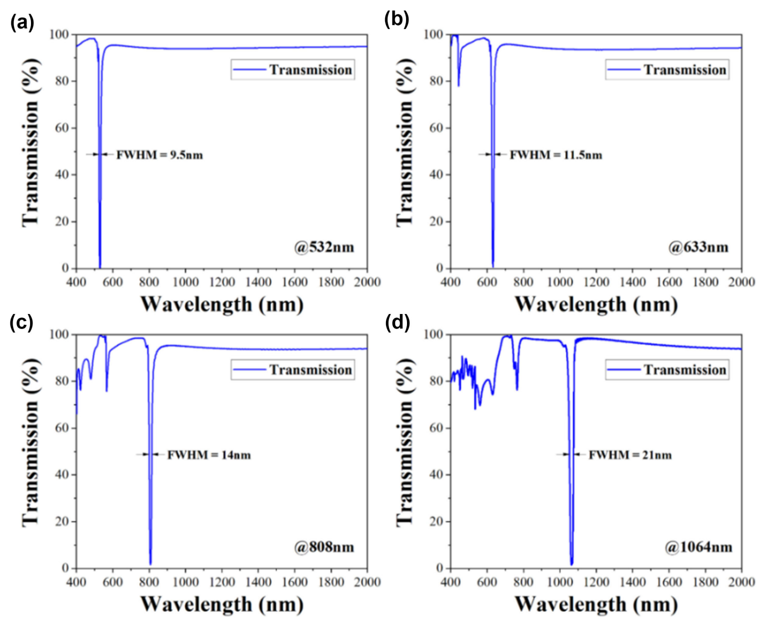

Fig. 2. The transmission spectra of the all-dielectric metasurfaces with various structural parameters for narrowband notch filtering at specific wavelengths. (a) 532 nm. (b) 633 nm. (c) 808 nm. (d) 1064 nm.

3. Results and Analysis

The optimal structural parameters of the proposed all-dielectric metasurfaces for the frequently-used wavelengths (532 nm, 633 nm, 808 nm, 1064 nm) could be received by the appropriate merit functions and PSO method mentioned above, shown in Table 1. Figure 2 shows the transmission spectrums of the all-dielectric metasurfaces with the optimized structural parameters. The bandwidths of these metasurface notch filters are compressed significantly compared with those typical thin film notch filters, where the great reduction of ~50% can be observed. The full width at half maximum (FWHM) of our proposed notch filters are only 9.5 nm@532 nm, 11.5 nm@633 nm, 14 nm@808 nm, 21 nm@1064 nm, respectively, while the OD values of these filters are able to reach 2~4 with the optimized structures. And high transmission >93% is kept across the wavelength range [−300 nm, +900 nm] outside the targeted wavelength for all these metasurfaces, which constructs the excellent narrowband notch filter over VIS-NIR broadband range.

Apparently, the geometrical parameters have a large impact on the transmission/filtering feature of the proposed all-dielectric metasurface. Figure 3(a) displays the maps of transmission spectra when the diameter of the circle patch **D** is tuned from 200 nm to 400 nm. It is obvious that a red shift will occur when the dimension of the patch increases gradually with the dip transmission increasing simultaneously. The bandwidth of this structure will be reduced mostly at an intermediate value of

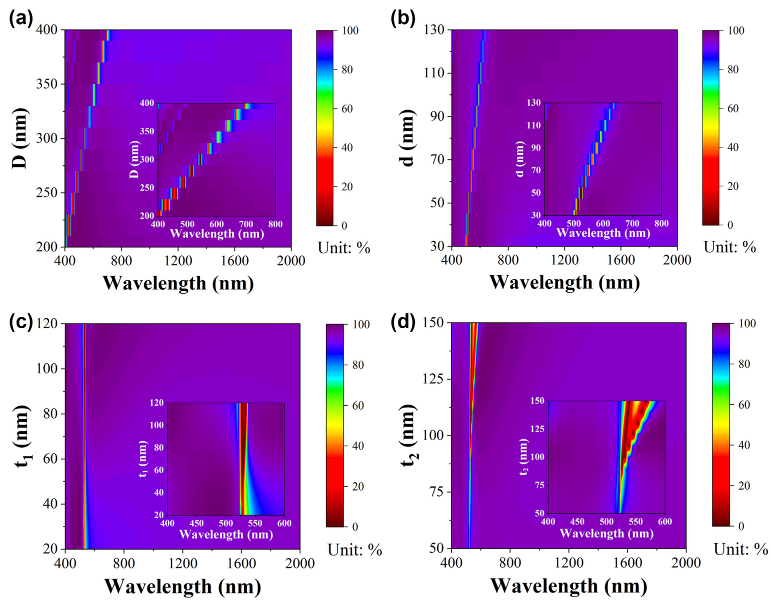

Fig. 3. Maps of transmission spectrums for the all-dielectric metasurface when (a) the diameter of the patch, (b) the interval between the patches, (c) the thickness of the top SiO_2 layer, (d) the thickness of the bottom TiO_2 layer are tuned. The parameters are set the same as the optimized notch filter discussed in Fig. 2(a) for 532 nm, if not particularly specified. The insets are detailed figures.

the diameter, ~300 nm. And small transmission dips come out at the short wavelengths because of the higher order under the condition of $p > \lambda$, where λ is the wavelength under consideration [15]. Then, the effect of the interval between the patches **d** is shown in Fig. 3(b). Similarly, the transmission spectrums present a red-shift phenomenon when the interval increases from 30 nm to 130 nm. Meanwhile, the dip transmission will rise with the increasing interval. And the bandwidth will increase within the interval range [30 nm, 50 nm] and decrease within the interval range [60 nm, 100 nm]. Both the diameter of the patch and the interval between the patches contribute to the period of the whole structure, so the increasing patch or interval results in the increasing period, leading to the red shift of the transmission spectrums [16]. The thickness of the top SiO_2 layer $\mathbf{t}_1$ has a great impact on the transmission bandwidth and the dip transmission, shown in Fig. 3(c). In fact, the top SiO_2 layer acts as the anti-reflection layer for the bottom high index layer, which will be discussed in the following section. The dip transmission will be reduced distinctly when the top SiO_2 layer is added and the thickness grows up. But the bandwidth will broaden with the increasing thickness of top SiO_2 layer. Therefore, the thickness of the top SiO_2 layer is designed to comprise the transmission and the bandwidth. Figure 3(d) shows the influence of the thickness of bottom TiO_2 layer $\mathbf{t}_2$ on the transmission/filtering property. The thickness of the bottom TiO_2 layer should be thick enough ($\mathbf{t}_2 > 75$ nm) to achieve the efficient notch filtering at specific wavelength. As the thickness of the bottom TiO_2 layer increases from 75 nm to 115 nm, more light at the center wavelength will be suppressed while the bandwidth will be broader. And it is noted that additional dip will appear within dip transmission band with the broader bandwidth, i. e. w-shape dip transmission will come out when the thickness of the bottom TiO_2 layer increases. Also, the transmission curve will move towards to the longer wavelength (red-shift) slightly with the increasing wavelength, which is beneficial for the subtle adjustment of the center wavelength of the dip transmission for this all-dielectric metasurface.

Then, the effect of the top SiO_2 layer on the transmission/filtering performance of the proposed all-dielectric metasurface is studied. Figure 4(a) shows the schematic diagram of the metasurface comprised by single-layer patch array of high refractive index without the top low index layer. The incident light illuminates the structure from the metasurface side and transmitted through the

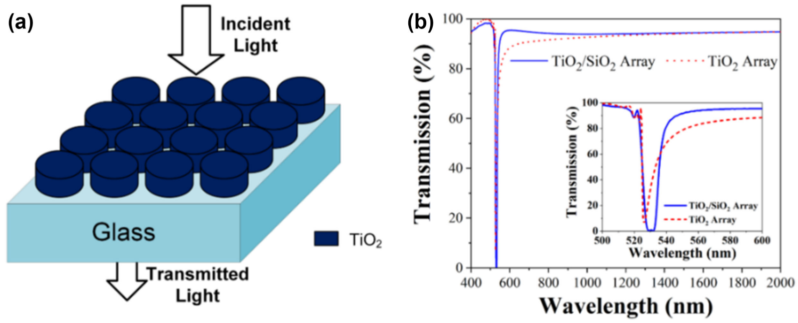

Fig. 4. (a) Geometry of the single-layer dielectric metasurface for narrowband notch filtering without the top SiO_2 layer. (b) The transmission of the two metasurfaces with/without the top SiO_2 layer and the inset is the detailed figure.

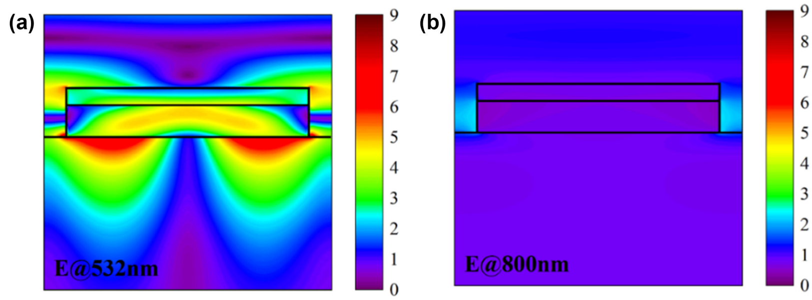

Fig. 5. The electric field amplitude of the structure with the set of optimal parameters mentioned above for 532 nm notch filter at the filtering wavelength and the high-transmission wavelength. (a) 532 nm. (b) 800 nm.

substrate as same as that in Fig. 1. The transmission spectra of the two metasurfaces with/without the top SiO_2 layer is depicted in Fig 4(b), and the detailed curve across the wavelength range [500 nm, 600 nm] is the inset figure. The notch filtering feature of the single-layer TiO_2 metasurface can be observed clearly. But without the top low index layer, the transmission of the notch filtering wavelength will be raised up to 7% and less (only 78%$\sim$88%) light across the outside wavelength range [550 nm, 600 nm] will pass through the structure. Moreover, the asymmetry of the transmission feature around the notching filtering wavelength become much more evident, which will severely restrict the noise-to-signal ratio of the system equipped with this notch filter. So, the top SiO_2 layer is the antireflection layer for the single-layer TiO_2 metasurface, which leads to similar bandwidth, lower transmission at notch filtering wavelength and higher transmission at other wavelengths.

To reveal the physical origin of the spectral filtering feature of the proposed all-dielectric metasurface, the electric field distribution is researched. Figures 5(a)-(b) illustrate the electric field profile of the structure with the optimal parameters for the 532 nm notch filter at the center wavelength $\lambda = 532$ nm and high transmission wavelength $\lambda = 800$ nm. From Fig. 5(a), it can be seen that for the center wavelength ($\lambda = 532$ nm), there is an intense coupling between the low index zone (air/hole) to the high index zone (TiO_2 patch), exciting a drastic resonance in the TiO_2 patch, resulting in $\sim$100% light at resonance wavelength reflecting back to the incident environment. Such resonance excited within the periodic structure with high index and low index materials orderly arranged here is so-called Fano resonance [17, 18]. This optical Fano resonance works similar to an interference effect: incident light illuminates on a periodic structure to excite the localized mode supported by the periodic surface (high/low index structure) and the localized mode leaks into the surrounding environment. The leaking light encounters with the directly reflected light from the surface and if the condition of the constructive interference (the same phase for the reflected and leaking light) is matched, a sharp reflectance peak will occur [18], [19]. Different from the behavior of the center wavelength, nearly all (>93%) the incident light for the high-transmission wavelength ($\lambda = 800$ nm) pass through the metasurface directly without the coupling with different index zones and the resonance within the high index zone. As a result, the Fano resonance excited by the all-dielectric metasurface is responsible for the efficient blocking at specific wavelength and high transmission at other wavelengths.

4. Conclusion

In conclusion, a novel scheme of an all-dielectric metasurface with double-layer patch array is proposed to achieve the highly tunable, narrowband notch filtering across VIS and NIR range. The proposed all-dielectric metasurface is able to achieve deep blocking at specific wavelength while allowing other light passing through with high efficiency. With the optimal structure of the all-dielectric metasurface, the bandwidth can be greatly compressed, which is only ~50% of the typical filter for distinctive wavelengths. Moreover, the effect of the geometrical parameters on the transmission/filtering properties is analyzed and a distinct relationship is provided to design the desired narrowband notch filter conveniently. And with the top low index layer, the anti-reflection layer, the notch filter can achieve narrower bandwidth, lower transmission at notch filtering wavelength and higher transmission at other wavelengths. Through the analysis of the electric field of the structure, the physical origin of the phenomenon is verified that Fano resonance excited by the all-dielectric metasurface leads to the deep blocking feature at the specific wavelength and high transmission at other wavelengths of this all-dielectric metasurface. The proposed all-dielectric metasurface, potentially produced by nanoimprint technology [20] with high and low index polymer materials, can have applications in optical communication, spectroscopy, laser-protection and so forth.

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