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Ag nanoprism metamaterial based tunable plasmonic logic gate

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Abstract

A metamaterial comprised of asymmetrically arranged Ag nanoprisms has been proposed and investigated in this paper. The metamaterial shows a polarization dependent PIT effect. The metamaterial with its periodic length along a *y*-axis less than 400 nm shows two tunable transmission dips. When the periodicity is increased above 400 nm, the metamaterial shows three adjustable transmission dips against the polarization state. By choosing different wavelengths of incident light, the metamaterial can be used as plasmonic Boolean logic gates. The working wavelengths of these plasmonic devices can then be adjusted by controlling the fillet radius of Ag nanoprism in metamaterial. These results offer great potential in developing polarization dependent tunable plasmonic information processing devices.

Keywords: PIT effect, metamaterial, Boolean logic gate

(Some figures may appear in colour only in the online journal)

1. Introduction

Metamaterials composed of periodic metallic nanoparticles and nanostructures have attracted extensive attention, due to their unique optical properties which do not exist in nature including negative refractive index [1, 2], Fano resonance [3], and perfect absorption [4]. Plasmon induced transparency (PIT) in metamaterials is an exceptional Fano resonance and an analogy of atomic electromagnetically induced transparency [5, 6]. The PIT effect can be attributed to the destructive interference of two resonances with different line widths [7]. In recent years, different kinds of metamaterials have been proposed and studied to realize PIT and applied in plasmonic sensors [8, 9], slow-light devices [10, 11], and switches [12, 13]. Polarization state as an important characteristic of light can be modulated using metamaterials with such unique optical responses. Various metamaterials have been proposed as polarization control devices, including wave plates [14], polarization rotators [15], and cross-polarization converters [16]. However, little attention on metamaterials has been paid to construct a planar plasmonic information processing device with different polarization states.

Recently, metal nanoprism with high structural symmetry and strong geometric anisotropy has been widely studied as an important building-block of metamaterial [17, 18]. These nanoprism metamaterials show PIT and giant slow light effects. Nanoprism dimer shows polarization dependent local density of states, the tunable modal distribution make the dimer to become novel design of plasmonic information processing device (i.e. Boolean logic gate) [19]. However, metal metamaterials with variously arranged nanoprism still need to be further designed and studied to realize novel plasmonic Boolean logic gates. The optical properties of metal metamaterials are usually fixed once they are prepared, and a lot of efforts have been made to break this limit by changing the materials' permittivity in the metamaterials [20–22]. It is well known that Ag nanoprism can be easily filleted due to the sensitivity of Ag atom to the surrounding environment [23–25]. So combining metamaterials with Ag filleted nanoprism provides a new method to adjust the optical properties of metamaterials due to the dependence on their geometry structures. The periodic Au nanoprism array can be prepared through the self-assembly method, which makes the combination between nanoprism and metamaterial become promising [26]. Through controlling the purity of Au nanoprism and the processing precision of the template, the nanoprism metamaterial with precise geometry can be obtained.

In this paper, the metamaterial composed of asymmetrically arranged Ag nanoprism was proposed and investigated by the finite element method. The metamaterial has a smaller periodicity along the y-axis and shows two tunable transmission dips against the polarization direction of incident light. The wavelengths of these dips could be adjusted by manipulating the fillet radius of Ag nanoprism. The metamaterial with larger periodicity showed three polarization dependent transmission dips with different trends. By choosing specific wavelengths and polarization angles of the incident light, the asymmetrical Ag nanoprism metamaterial can be used for various Boolean logic gate applications.

In the following content, the structure model and numerical method of the Ag nanoprism metamaterial are shown in section 2. In section 3, the impact of polarization direction of incident light on the PIT effect of Ag nanoprism metamaterial with shorter period is firstly investigated. The functionalization of the tunable PIT effect is researched. The working wavelengths of the Boolean logic gates are adjusted through changing the fillet radius of Ag nanoprism. The effects of the periodic length on the PIT effect of the metamaterial are then investigated. The Boolean logic gates realized by longer period metamaterial are proposed. Finally, section 4 shows a summary of all results.

2. Structure model and numerical method

The metamaterial as schematized in figure 1 is composed of asymmetrically arranged Ag nanoprisms (grey). The asymmetrical nanoprism array was placed on silica substrate (purple), and the interface was on x-y plane at $z = 0$ nm. The metamaterial was covered with air ($n = 1$). Both air and the silica substrate were semi-infinite. The metamaterial possesses a rectangular lattice as shown in figure 1(a). The periodic length along the x-axis (P_x) in this work was fixed at 385 nm to ensure the continuity of Ag nanoprisms, however, the periodic length along the y-axis (P) was varied from 150 nm to 800 nm. The influences of P on the optical properties of the metamaterials were researched.

As shown in figure 1(b), four Ag nanoprisms in the unit cell possess the same geometric parameters. The angles between the angular bisectors of the four nanoprisms (the magenta dashed lines) and the x-axis are 30°, 60°, 90°, and 120°, corresponding to the order from left to right, respectively. Due to the sensitivity of silver atom to its surrounding environment [27–29], the tips of Ag nanoprism were carefully filleted. So Ag nanoprism in the metamaterial can be described by the thickness, h, the edge length, L, and the fillet radius, r. The values of L and h were fixed at 100 nm and 10 nm, respectively. The value of r could be used as a variable to quantify the effect of the change in the surrounding. To investigate the effect of its surrounding environment, the optical properties of the Ag nanoprism metamaterial with different fillet radius were studied.

The optical properties of the metamaterials in this paper were simulated using the finite element software (Comsol Multiphysics). The range of wavelength of the incident light was taken between 500 nm and 1000 nm and varied in steps of 4 nm. The material of nanoprism in metamaterial was Ag, and its frequency dependent refractive index was obtained from the experimental data of Johnson and Christy [30]. The dielectric function of silica for the substrate was from Palik [31]. The linearly polarized light (the rainbow arrow) illuminates the surface of Ag nanoprism along the negative direction of z-axis as shown in figure 1(a). In figure 1(b), the angle between the polarization direction of incident light and the x-axis was defined as the polarization angle θ. To study the impact of the polarization state of incident light on the metamaterial, the optical properties of the metamaterial with θ increasing from 0° to 90° were discussed hereinafter.

3. Results and discussion

The optical properties of Ag nanoprism metamaterials under illumination of linearly polarized light were investigated. The polarization angle θ was varied from 0° (along x-axis) to 90° (along y-axis), while other structural parameters were fixed. The transmission spectra of Ag nanoprism metamaterial versus θ are shown in figures 2(a) and (b). The metamaterial with $P = 200$ nm shows a typical PIT effect and possesses two transmission dips in the spectra. This PIT effect originates from the destructive interference between the two plasmonic modes at the resonant wavelengths of two dips. So the PIT can be modulated by tuning the resonant intensities of the two plasmonic modes. The dip in shorter wavelength region is labelled as dip1, and for the longer wavelength is marked as dip2. As θ increases from 0° to 90°, dip1 is initially unchanged and then slightly blue-shifts. Finally, dip1 stabilizes as θ is increased above 75°. The transmissivity of dip1 does not get affected by the change of θ. For a particular wavelength of incident light, its transmissivity also changes as θ varies. The transmissivity of incident light at 656 nm increases from 0.07 ($\theta = 0°$) to 0.61 ($\theta = 90°$).

Electric field distributions at dip1 with θ equal to 0° or 90° are shown in figures 2(c) and (d), respectively. The enhanced electric fields at the dip1 are mainly localized around the tips of Ag nanoprisms along the polarization direction of incident light. The enhanced electric fields around Ag nanoprisms couple with each other along the x-axis, which can be seen as a continuous plasmonic mode. As θ changes from 0° to 90° (i.e. the polarization direction varies from the x-axis to y-axis),

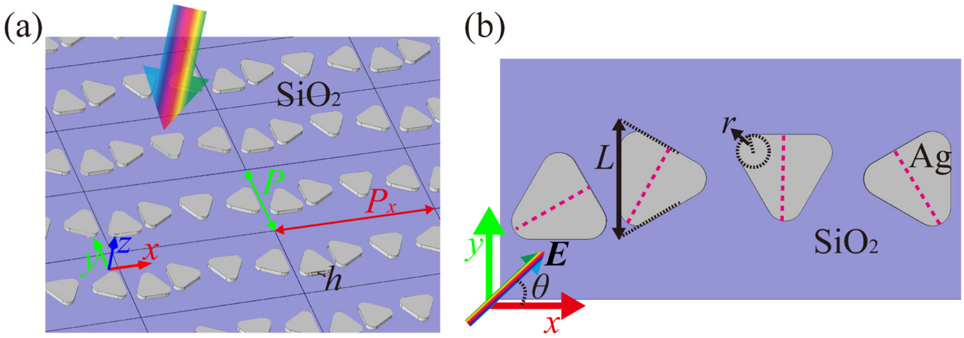

Figure 1. (a) Schematic diagram of Ag nanoprism metamaterial, (b) vertical-view of the unit cell, $L = 100$ nm, $h = 10$ nm, $P = 200$ nm, $P_x = 385$ nm, and $r = 15$ nm.

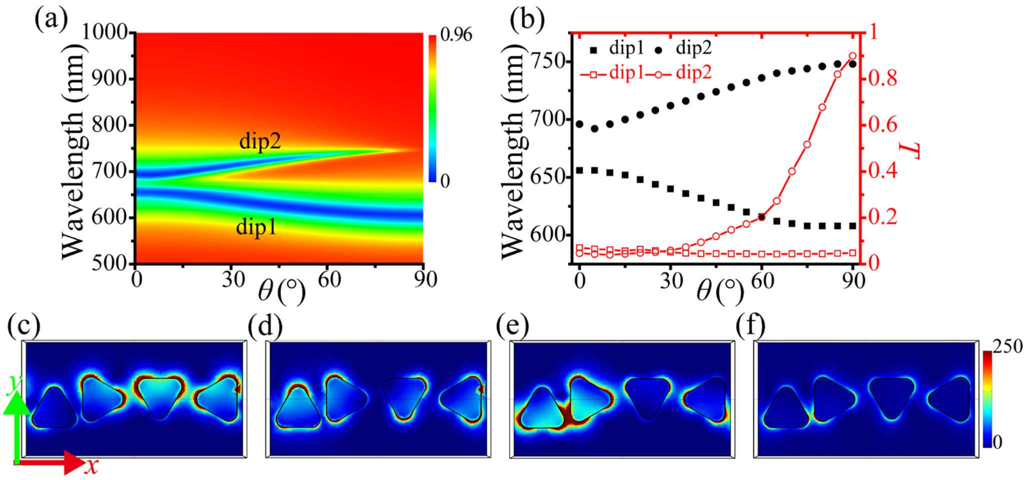

Figure 2. Transmission spectra of Ag nanoprism metamaterial with $P = 200$ nm. (a) Transmissivity (T) map versus θ and wavelength. (b) Resonant wavelength (black scatter plots) and transmissivity (red lines) spectra of dip1 and dip2 against θ. The square and circle dotted curves are dip1 and dip2, respectively. Electric field distributions in the x-y plane at $z = 0$ nm at the wavelength of two dips. (c) $\theta = 0°$, dip1; (d) $\theta = 90°$, dip1. (e) $\theta = 0°$, dip2; (f) $\theta = 90°$, dip2. The color bar ranges from 0 to 250.

the enhanced electric field region shifts from the tips of Ag nanoprisms along the x-axis to that along the y-axis. Although, the regions of the enhanced electric field shifts against θ, the electric field always interacts with each other to keep the continuous plasmonic mode. The interactions between Ag nanoprisms along x-axis are realized by the electric field coupling between their different tips as θ changes. This leads to the decrease of the equivalent resonant length of this plasmonic mode, and then the resonant wavelength of dip1 blue-shifts. The enhanced electric fields around tips are still strong when varied against θ, and likewise, the intensity of the plasmonic mode remains strong. The transmissivity of dip1 shows a tiny variation against the polarization angle of the incident light.

The dip2 firstly blue-shifts and then red-shifts gradually as θ is varied from 0° to 90°. However, its transmissivity (T) firstly stabilizes and then exponentially increases. The electric field distributions of this dip are shown in figures 2(e) and (f). As θ is increased, the enhanced electric fields are also localized around the tips of Ag nanoprism that are parallel to the polarization direction of incident electric field. Ag nanoprisms interact with each other to form another continuous plasmonic mode through the coupling of the enhanced electric fields. When θ is equal to 90°, the enhanced electric fields around Ag nanoprisms weaken dramatically. Therefore, the interaction strength between Ag nanoprisms decays, and the plasmonic mode disappears. The transmissivity of incident light at 696 nm increases from 0.05 ($\theta = 0°$) to 0.74 ($\theta = 90°$). Based on the polarization dependent transmission effect, the metamaterial with $P = 200$ nm can be used for a building block of larger plasmonic information processing architectures, as shown in table 1.

Table 1. Summarizing the AND gates accomplished by different wavelengths of incident light for the metamaterial with $P = 200$ nm.

θ (°)	θ (°)	Input code		AND gate					
		θ	θ	$T_{656\ nm}$	$T_{656\ nm}$	T_t	$T_{696\ nm}$	$T_{696\ nm}$	T_t
0	0	0	0	0.07	0.07	0	0.05	0.05	0
0	90	0	1	0.07	0.61	0	0.05	0.74	0
90	0	1	0	0.61	0.07	0	0.74	0.05	0
90	90	1	1	0.61	0.61	1	0.74	0.74	1

Two incident light of identical intensities and wavelengths but independently chosen linear polarizations illuminate the metamaterial. The polarization direction of the incident light 0° encodes as the 0 input, and 90° encodes as the 1 input. For a binary coding, the total transmitted intensity of two light (T_t) above a threshold (the initial incident intensity of single light)

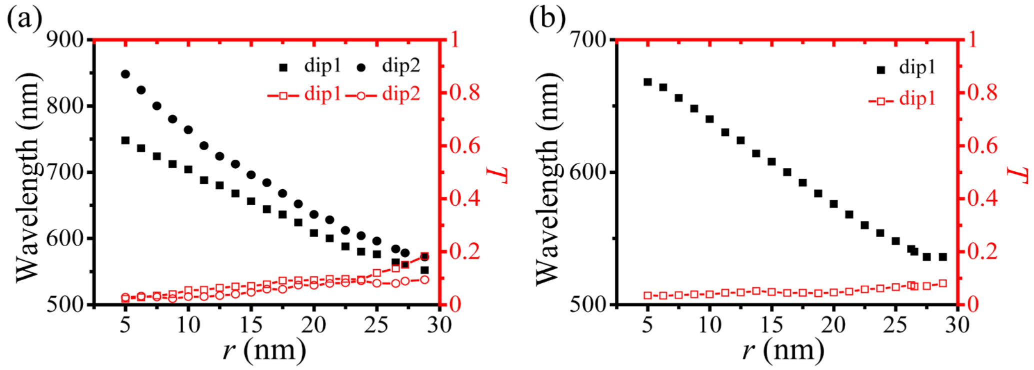

Figure 3. Resonant wavelength (black scatter plots) and transmissivity (red lines) spectra of Ag nanoprism metamaterial for $P = 200$ nm against r. (a) $\theta = 0°$, (b) $\theta = 90°$. The square dotted curves are dip1, and the circle dotted curves are dip2.

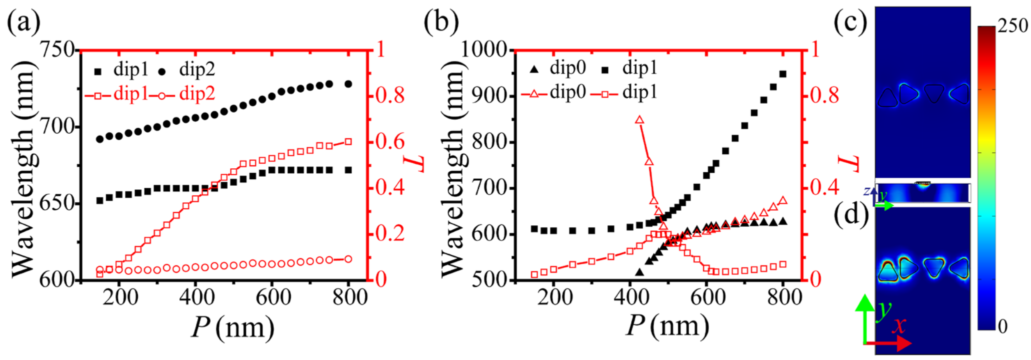

Figure 4. Resonant wavelength (black scatter plots) and transmissivity (red lines) spectra of Ag nanoprism metamaterial versus P. The square and circle dotted curve are dip1 and dip2, respectively. (a) $\theta = 0°$. (b) $\theta = 90°$. Electric field distributions on the x-y plane at $z = 0$ nm of dip0 for $P = 500$ nm. (c) $\theta = 0°$; (d) $\theta = 90°$. The color bar ranges from 0 to 250. The inset map is on the y-z plane at $x = 0$ nm, and its color bar ranges from 0 to 50.

encodes as the 1 output, the lower intensity is the 0 output. The binary responses of the metamaterial under the illumination of particular wavelengths of two incident light have been summarized in table 1. The light at 656 nm and 696 nm are chosen to realize an AND gate, respectively. By choosing different wavelengths of the incident light, the plasmonic Boolean gate (AND gate) has been realized by the Ag nanoprism metamaterial with $P = 200$ nm.

Because Ag atom is easily oxidized, Ag nanoprisms in this metamaterial can be easily filleted by manipulating their surrounding environment, so that the optical property of Ag metamaterial can likewise be changed [32]. Similarly, the wavelengths of its transmission dips can be tuned through varying the fillet radius of Ag nanoprism, r, in metamaterial. The influence of the fillet radius of Ag nanoprism to the transmission spectra of the metamaterial with $P = 200$ nm is shown in figure 3. In figure 3(a), the two dips for $\theta = 0°$ blue-shift as Ag nanoprisms in metamaterial are filleted. Moreover, the transmissivities of the two dips gradually rise when varied against r. This effect can be attributed to the waning interaction between the Ag nanoprisms, which originates from the increasing distance between the filleted nanoprisms in the metamaterial.

There only exists dip1 in the transmission spectrum of Ag nanoprism metamaterial for $\theta = 90°$ in figure 3(b). Dip1 shows a linear blue-shift effect and then becomes constant as r increases, while the transmissivity slightly increases. When θ is equal to 90°, dip2 always disappears. The wavelengths of the two dips for θ equal to 0° or 90° can be adjusted as r is carefully manipulated. Due to the linear relation between the fillet radius of Ag nanoprism and the concentration of the analytes, the Ag nanoprism with particular fillet radius can be obtained by carefully controlling the concentration of the analytes [33]. So the working wavelength of the Boolean logic gate can be adjusted in visible and near-infrared region by changing the fillet radius of Ag nanoprism (i.e. its surrounding environment) in metamaterial. By choosing suitable structural parameters of the metamaterial, the plasmonic Boolean logic gate can be realized at common telecommunication channel.

Since Ag nanoprisms interact with each other along the x-axis resulting in a continuous plasmonic mode, Ag metamaterial with varying periodicity along the y-axis can be considered as a grating with different periodic lengths. The wavelength and transmissivity spectra of the metamaterials with different periodic lengths are shown in figure 4. The metamaterial with $\theta = 0°$ shows two transmission dips in figure 4(a). The resonant wavelength of dip1 increases slowly and then stabilizes with enlarging P from 150 nm to 400 nm. As P further increases from 600 nm, dip1 red-shifts slowly and stabilizes again. The transmissivity of dip1 is firstly strengthened linearly in the first stage (P ranges from 150 nm to 400 nm) and then increases slowly in the second stage (P increases from 400 nm to 800 nm). The resonant wavelength of dip2 red-shifts slightly versus P. Also, its transmissivity

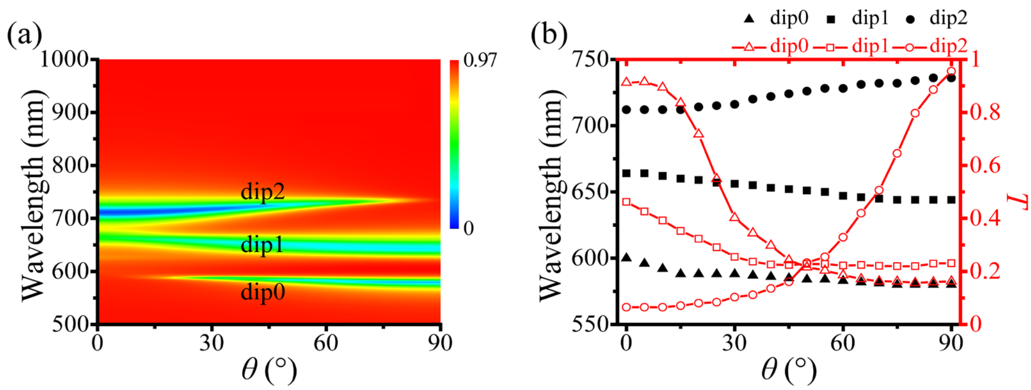

Figure 5. Transmission spectra of Ag nanoprism metamaterial with $P = 500$ nm. (a) Transmissivity map versus θ and wavelength. (b) Resonant wavelength (black scatter plots) and transmissivity (red lines) spectra for three dips. The triangle dotted curve is dip0, the square dotted curve is dip1, and the circle dotted curve is dip2.

gradually strengthens throughout. This result implies that the metamaterial with $\theta = 0°$ is equivalent to two plasmonic modes with different resonant lengths. The resonant strengths of two plasmonic modes can be modulated through manipulating the periodicity along the *y*-axis.

As shown in figure 2(a), the dip2 for $P = 200$ nm disappears when $\theta = 90°$. This can be attributed to the fact that its corresponding plasmonic mode is suppressed. The resonant wavelength and transmissivity spectra of the metamaterials with different periodic lengths and $\theta = 90°$ are shown in figure 4(b). The dip2 disappears against P throughout. There only exists dip1 when P is less than 400 nm. The wavelength of dip1 remains the same, and its transmissivity gradually becomes larger with P varying from 150 nm to 400 nm. Moreover, its wavelength shows an exponential red-shift effect as P is further increased from 400 nm. Its transmissivity first declines and then stabilizes. For P larger than 400 nm, the reduced transmissivity of dip1 can be attributed to a hybrid mode which is caused by the gradually enhanced coupling between its original plasmonic mode and waveguide mode. For $\theta = 90°$, dip1 always exists regardless of the periodic length along the *y*-axis.

Furthermore, a new dip (dip0) appears in shorter wavelength region, shown in figure 4(b). Firstly, the dip0 redshifts and then stabilizes as P increases further from 400 nm to 800 nm. Moreover, its transmissivity declines quickly and then slowly strengthens. The variation of electric field distribution of dip0 with θ, for $\theta = 0°$ or 90° are shown in figures 4(c) and (d), respectively. The metamaterial with P larger than 400 nm shows a new resonant mode (dip0) in figure 4(d). The new mode is a hybrid mode caused by the inter-coupling between the new plasmonic mode and the waveguide mode, as shown in the inset map of figure 4(d). This coupling originates from the matching between the new plasmonic mode and waveguide mode. The transmissivity of dip0 reaches the minimum when the resonant intensity of the hybrid mode reaches maximum with $P = 500$ nm (i.e. the plasmonic mode matches with the waveguide mode). So as P increases, the coupling strength becomes stronger firstly and then weaker, and the transmissivity firstly weakens and then strengthens. However, when θ is equal to 0°, the resonant strength of the new mode in figure 4(c) is so small that it causes the disappearance of dip0 in figure 4(a).

Table 2. Different Boolean logic gates based on different wavelengths of light and the metamaterial with $P = 500$ nm.

		Input code		OR gate			NAND gate		
θ (°)	θ (°)	θ	θ	$T_{712\,nm}$	$T_{712\,nm}$	T_t	$T_{580\,nm}$	$T_{580\,nm}$	T_t
0	0	0	0	0.07	0.07	0	0.94	0.94	1
0	90	0	1	0.07	0.94	1	0.94	0.16	1
90	0	1	0	0.94	0.07	1	0.16	0.94	1
90	90	1	1	0.94	0.94	1	0.16	0.16	0

When P is less than 400 nm, the metamaterials with θ equal to 0° and 90° possess two dips (dip1 and dip2) and one dip (dip1), respectively. Through manipulating the wavelengths of the incident light, the shorter periodic length metamaterial has potential to be plasmonic Boolean logic gates. When P is larger than 400 nm, the metamaterial with $\theta = 0°$ possesses two dips (dip1 and dip2), and the metamaterial with $\theta = 90°$ also shows two dips (dip0 and dip1). So the longer periodic length metamaterial can also be used to realize other kind Boolean logic gates, and this is discussed later.

To confirm the aforementioned conjecture about the longer periodic length metamaterial, the optical properties of the metamaterial under the illumination of different polarized light were obtained and shown in figure 5. The metamaterial with $P = 500$ nm shows three dips in figure 5(a). As θ varies from 0° to 90°, the dip0 appears and slightly blue-shifts, and its transmissivity declines quickly in figure 5(b). The other two dips for $P = 500$ nm show similar variation tendencies as that with $P = 200$ nm. Dip1 also slightly blue-shifts against θ, but its transmissivity weakens throughout. Moreover, dip2 slightly red-shifts and disappears as θ reaches 90°, and its transmissivity increases correspondingly. The incident light at the wavelength of dip0 with $\theta = 0°$ can propagate through the metamaterial. However, the incident light at the wavelength of dip0 cannot traverse through the metamaterial with $\theta = 90°$.

By choosing the wavelengths of incident light, the metamaterial with $P = 500$ nm can be used for other Boolean logic gates. Two incident light of identical intensities and wavelengths but independently chosen θ illuminate the metamaterial. The polarization direction of the incident light θ of 0° (90°) is ascribed as 0 (1) binary code. The total transmitted intensity of two light (T_t) is 0 (1) code if it is below (above) the initial incident intensity of single light. The binary responses have been shown in table 2. Two light at 712 nm are chosen to realize an OR gate. Two light at 580 nm are used to obtain an NAND gate. Through choosing different wavelength of incident light, the Ag nanoprism metamaterial with $P = 500$ nm realizes NAND gate and OR gate. Through carefully choosing the fillet radius of Ag nanoprism, the above logic gates can be realized by the commercial monochromatic light. The monochromatic light can be produced by the monochromatic source or the band-pass filter with a wide band source which are available in the market.

4. Conclusions

In conclusion, metamaterial composed of periodic Ag nanoprism that possesses a polarization dependent PIT effect has been shown in this paper. The metamaterial with P less than 400 nm shows two transmission dips in visible and near-infrared regions which originate from two plasmonic modes. The dip in longer wavelength region fades away when the polarization angle of incident light is varied from 0° to 90°. When P is larger than 400 nm, the transmission spectrum of the metamaterial shows a new dip in the shorter wavelength region. The new dip originates from a hybrid mode from the inter-coupling between the new plasmonic mode and the waveguide mode. The hybrid mode gradually weakens as the polarization angle ranges from 0° to 90°, and the transmissivity of the new dip decreases. Based on the transmission characteristic of the metamaterial, a series of novel plasmonic logic architectures are proposed. Due to the sensitivity of the Ag atom to the surrounding environment, the operating wavelength of the Boolean logic gate can be adjusted by manipulating the surrounding environment of the metamaterial. This tunability effect breaks a limit of typical metamaterials in practical applications that their optical properties are fixed once the metamaterials prepared. The metamaterials with different periods have potential to be used for tunable plasmonic modal Boolean logic gates.

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