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Enhanced transmission performance based on ultrathin broadband circular hole array metasurface

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Abstract

A high transmittance broadband metasurface with Si and STO layers is verified in 100–130 THz. This metasurface achieves a transmission peak (Amplitude 78.1%, Resonance frequency 112.2 THz) with a complete Si layer, or a broad transmission band (Average transmittance 82.3%, bandwidth 5.1 THz) with a Si layer defined by a circular hole array. The influence of structural parameters (period P and diameter D) on this transmission band is measured. In the first set of measurements, the average transmittance and bandwidth of this metasurface remain unchanged with P increasing. In the second set of measurements, however, the average transmittance is increased from 82.3% to 92.7%, and bandwidth is enhanced from 5.1 THz to 7.2 THz with D increasing. Finally, the sensitivity of the metasurface to temperature is measured. When temperature increases from 300 K to 360 K, average transmittance increases from 82.3% to 95.4%, and bandwidth enhances from 5.1 THz to 10.3 THz. When temperature reduces, the average transmittance and bandwidth decrease. This metasurface exploits the potential of temperature sensing.

1. Introduction

High-transmission metamaterial or metasurface have always attracted researchers’ interest. This is because many functional devices can be developed based on high-transmission metamaterial or metasurface [1–4]. In the early stages of research, various structural design strategies are used to develop metamaterial with high transmission properties. For example, metal cutting line structural strategy shows a high transmission peak around 1.3 THz, its FOM reaches 23 [5]. Combining phase change materials with metamaterial is a popular method for developing high-transmission metamaterial. Vanadium dioxide (VO2) is a temperature-sensitive material, which exhibits dielectric properties at temperature below 68 °C and metal conduction properties at temperature up to or above 68 °C. Therefore, the transmission properties of metamaterial with VO2 can be modulated by changing temperature. This method of enhancing the transmissivity of metamaterial shows an outstanding advantage: only the external conditions (such as temperature) need to be changed without structural parameters, which is beneficial to practical application [6–8]. Extraordinary optical transmission (EOT) resonance is also a common method for developing high-performance metamaterial [9]. In recent years, new methods and materials are verified during the development of metamaterial or metasurface. For example, it is a novel design idea to replace the common metal materials with Dirac semimetal in metamaterial or metasurface. The resonance properties of the metasurface can be modulated by changing Fermi level of the Dirac semimetal [10]. Another popular new material is graphene. Metasurface based on graphene shows the sensitivity to Fermi energy [11, 12]. New mechanisms to improve the transmission properties of metasurface are electromagnetically induced transparency (EIT) and plasmon-induced transparency (PIT) effects [13–15]. Application of new materials and mechanisms can greatly improve transmission properties of metamaterial or
metasurface. Silicon is often used as a dielectric layer in the design and development of high-performance metamaterial or metasurface. Moreover, the influence of the resonance properties of the silicon layer on the transmission properties of metasurface is also the focus of researchers. Although Si is a typical dielectric, it has the characteristics of the photoelectric medium in some frequency bands and shows localized plasma polarization behaviors. This localized plasma polarization behavior is mainly excited by the coupling between the electromagnetic wave and local collective charge oscillation on the surface of Si layer.

In this paper, a high-performance broadband metasurface with Si and STO layers is designed and verified. The STO layer is also a temperature-sensitive material. Its dielectric properties can be modulated by temperature. However, this STO layer, unlike the VO2 layer, has no phase change properties, which is more conducive to the sustained control of metasurface properties. Moreover, the Si layer plays an important role in the transmission properties of the metasurface. When the Si layer in the metasurface is complete, a transmission peak can be obtained in the measurement spectrum, while the Si layer is defined by a circular hole array, a transmission band is obtained. The effect of structural parameters (period $P$ and diameter $D$) on this transmission band is measured in experiments. Finally, the transmission properties of the metasurface are measured during heating and cooling.

2. Design and experiments

2.1. Design of unit cell

To illustrate the structural characteristics of samples, figures 1 (a), (b) shows the top view and a cross-sectional view of the unit. The proposed unit cell contains four materials: the top metal layer is a silver layer, which is patterned by a round holes array. The intermediate dielectric layers are a silicon (Si) layer patterned by the same round holes array and a complete SU-8 layer. The bottom layer is a complete STO layer. All simulations are revealed by HFSS. Boundaries of the unit cell adopt the idealized electromagnetic boundaries. The scanning frequency of simulation is 0.01 THz. The top and bottom of the unit cell are perfectly matched layers respectively. The electromagnetic wave is set to vertical incident mode. And the structure parameters can be found in table 1. On the one hand, the metal layer can be described by the Drude mode. On the other hand, the STO layer can be described as follows [16]:

$$\varepsilon_w = \varepsilon_\infty + \frac{f}{\omega_0^2 - \omega^2 - i\omega\gamma}$$  \hspace{1cm} (1)

In the formula (2), $\varepsilon_\infty$ is set to be high-frequency bulk permittivity. $f = 2.6 \times 10^6 \text{ cm}^{-2}$ is set to be oscillator strength. The $\omega_0$ is set to be soft mode frequency:

$$\omega_0(T)[\text{cm}^{-1}] = \sqrt{31.2(T - 42.5)}$$  \hspace{1cm} (2)
And $\gamma$ is set to be soft mode damping factor:

$$\gamma(T) [\text{cm}^{-1}] = -3.3 + 0.094T$$ (3)

In formula (3), $T$ is set to be ambient temperature. In simulation, electromagnetic boundaries are set based on the reported work [17].

2.2. Experiment of samples

The measured samples are manufactured according to the following steps. In the experimental preparation stage, a piece of glass is selected as the temporary substrate, which should be cleaned by adopting ethanol and ultrapure water and dried by adopting C-MAG HP10 (baked for 4 min). First, a 2 $\mu m$ thick SU-8 layer will be spun (using this device: MSC-400Bz-6N spinner, the spin time will be adopted for 3.5 min, and the spin speed will be adopted for 2430 rpm) on the glass, and baked (using the device: C-MAG HP10, baking in advance for 2 min). Second, a STO layer will be deposited (using the device: ZZL-U400C, parameters: working pressure adopting $5 \times 10^{-10}$ (atm), vacuuming time adopting 6.5 h, and warm-up time adopting 52 min, adopting rate 2.6 $\AA$ s$^{-1}$) on the first SU-8 layer. Third, this semi-finished metamaterial will be soaked in acetone solution to remove the first SU-8 layer and achieve a free standing STO layer. Fourth, when the free standing STO layer is cleaned (also adopting ethanol and ultrapure water) and dried (also adopting C-MAG HP10, baked for 5 min), another SU-8 layer will be spun (using this device: MSC-400Bz-6N spinner, the spin time will be adopted for 4 min, and the spin speed will be adopted for 2550 rpm) on the STO layer and baked (using the device: C-MAG HP10, baking in advance and back for 2 min and 2.5 min). Fifth, a Si layer will be deposited (using the device: ZZL-U400C, parameters: working pressure adopting $5 \times 10^{-10}$ (atm), vacuuming time adopting 6 h, and warm-up time adopting 55 min, adopting rate 2.8 $\AA$ s$^{-1}$) on the SU-8 layer. Sixth, a metal layer will be deposited (using the device: ZZL-U400C, parameters: working pressure adopting $5 \times 10^{-10}$ (atm), vacuuming time adopting 5 h, and warm-up time adopting 45 min, adopting rate 2.2 $\AA$ s$^{-1}$) on the Si layer. Finally, the proposed round holes array will be patterned (using the device: CABL-9000C) on the metal and Si layers, as shown in figure 1(c). All samples will be cleaned through an ultrasonic (adapting device: VGT-QTD). Measured transmission results will be achieved through a Fourier spectrometer (adapting Bruker Optics Equinox 55). All photo of samples will be achieved through a Leica DM2700.

3. Measurement results and discussion

3.1. Physical mechanism of the transmission band

The result of the structure with a complete Si layer is shown in figure 2(a). A transmission peak with amplitude 78.1% is achieved at resonance frequency 112.2 THz when the Si layer is a complete piece of material. The simulated transmission peak reaches 89.3% at 112.3 THz, seen the red curve in figure 2(a). The measured transmission spectrum of the proposed samples is shown in figure 2(b). The measured transmission bandwidth is 5.1 THz, and the average transmittance in this band reaches 82.3%, seen the dotted area in figure 2(b). The simulated average transmittance is 86.4%, which is higher than the measured results, as shown in figure 2(b).
In the above formula (6), $f_o$ is set to be the resonance frequency, and $\Delta f$ is set to be the measured transmission bandwidth.

In order to reveal the physical mechanism of the transmission band in figure 2(b), electrical intensity distributions (defined as $|E|^2$ in this paper) are simulated. Figure 3 shows the electrical distributions on the cross section xoz. For the structure with a complete Si layer, the simulated electrical fields are mainly distributed on the edges of metal holes array, and two bright modes are obtained due to the coupling of the free charge on edges of the metal layer holes array with the electromagnetic field of the incident light, as shown in figures 3(a) and 4(a). These bright modes are coupled with each other in horizontal direction. The transmission peak in figure 2(a) results by these resonance behaviors. For the proposed structure, it is found that bright modes are excited on the edges of metal holes array, as shown in figures 3(b) and 4(b). Moreover, the bound charge at the edge of the Si layer holes array is coupled to the electromagnetic field of the incident light during the incident light passes through the Si layer, which results in the local surface plasma (LSP) mode excitation, as shown in figure 4(c).

$$Q = \frac{f_o}{\Delta f}$$

Figure 3. (a) Electric field intensity distributed on the cross section xoz of the samples with a complete Si layer at 112.2 THz. (b) Electric field intensity distributed on the cross section xoz of the samples with a defined Si layer at 113 THz.

Figure 4. (a) Electric field intensity of the samples with a complete Si layer at 112.2 THz on the xoy plane of the metal layer. (b) Electric field intensity of the samples with a defined Si layer at 113 THz on the xoy plane of the metal layer. (c) Electric field intensity of the samples with a defined Si layer at 113 THz on the xoy plane of the Si layer.
can be revealed by the resonance properties of the Si layer in samples, as follows:

\[ \varepsilon = (n + ik)^2 \]  

\[ (5) \]

In the above formula, \( \varepsilon \) is the permittivity, \( n \) is the refractive index, and \( k \) is the extinction coefficient. The real and imaginary parts of the permittivity are shown in figure 5. The real part of the permittivity is less than zero in the region 110.7 THz to 115.8 THz, which implies a ‘plasmonic range’ of the Si layer in this region. Therefore, bound charge is achieved on the inner surface of the Si layer holes array. These bound electrons undergo a collective oscillation under the action of external electromagnetic waves, which excites the LSP resonance effect and generates a strong local electric field on the inner surface of the silicon layer hole. These LSP modes are revealed on the edges of Si holes array, as shown in figures 3(b) and 4(c). The bright-bright modes coupling effect is found. Moreover, the coupling between bright and LSP modes is also achieved, as shown in figure 3(b). The plasmon hybridization phenomenon between bright and LSP modes enhances the transmission and excites the transmission band in figure 2(b). This plasmon hybridization phenomenon is based on the low quality factor of the resonant of the Si layer. It should be indicated that this coupling effect of bright and LSP modes between the metal and Si layers results in a higher distribution of electrical intensity \( |E|^2 \), which implies the EOT phenomenon is enhanced in the Si layer holes array. To describe this enhancement, electrical intensity \( |E|^2 \) enhancement factor is used, as follows:

\[ \sigma = \frac{|E_1|^2}{|E_2|^2} \]  

\[ (6) \]

In the equation above, \( |E_1|^2 \) is the electric field strength which is extracted from the point where the strength is the highest in figure 3(a), seen the black arrow, while \( |E_2|^2 \) is the electric field strength where the strength is the highest in figure 3(b), seen the black arrow. The extracted enhancement factor reaches 14.3, which implies that the electric field strength based on the coupling effect of bright and LSP modes between the metal and Si layers is 14.3 times the strength of the structure with a complete Si layer.

3.2. Influence of structural parameters

The effect of structural parameters on the transmission band is measured in experiments. Figure 6(a) shows the measured transmission spectrum with different \( P \), while the diameter \( D \) remains unchanged. The average transmission and bandwidth of samples remain unchanged with \( P \) increasing. Figure 6(b) shows the measured transmission spectrum with different diameter \( D \). In experiments, \( D \) is set to be 18.0 \( \mu \text{m} \), 18.4 \( \mu \text{m} \), and 18.8 \( \mu \text{m} \). The transmission band is shifted to higher frequencies. Bandwidth increases from 5.1 THz to 7.2 THz. The transmission is enhanced due to the diameter is increased, as shown in figure 6(b). Similar resonance behaviors can also be obtained through simulation, as shown in figure 7. This indicates that the increase in \( P \) does not significantly change the resonance intensity and frequency of LSP modes.

3.3. Effect of temperature on transmission band

Finally, figure 8 shows the effect of temperature on the transmission band. Three temperature points are selected, and each temperature test point is maintained for 5 min in experiments (No structural parameters change). It is found that the transmission band is enhanced with temperature increasing. This is because the STO layer is sensitive to temperature according to the formula (1). The real parts of permittivity and loss tangent are both shown in figure 9. It is found that the real part will be reduced due to the measured temperature increasing.
Figure 6. (a) Measured transmission result of samples with different $P$. (b) Measured transmission result of samples with different $D$.

Figure 7. (a) Simulated transmission result of samples with different $P$. (b) Simulated transmission result of samples with different $D$.

Figure 8. The measured transmission spectrum with temperature increasing.
Based on the perturbation theory [18–20]:

$$\frac{\Delta \omega}{\omega} = \frac{\omega - \omega_b}{\omega_b} \approx \frac{-\iiint \left[(\Delta \varepsilon \cdot \vec{E}) \cdot \vec{E}_0 + (\Delta \mu \cdot \vec{H}) \cdot \vec{H}_0\right] dV}{\iiint (\varepsilon |\vec{E}_0|^2 + \mu |\vec{H}_0|^2) dV} \quad (7)$$

Where, $\Delta \varepsilon$ is the difference of the real part, $\Delta \mu$ is the difference of permeability. $\vec{E}_0$ and $\vec{H}_0$ are set to be the unperturbed electric and magnetic fields. $\vec{E}$ and $\vec{H}$ are set to be the perturbed electric and magnetic fields. When temperature increases, the $\Delta \varepsilon$ is negative value, which leads to the resonance frequency increase and transmission band shift to higher frequencies according to the formula (7). Moreover, as the measured temperature increase, the energy loss reduces based on the loss tangent of the STO layer, as shown in figure 9. Therefore, the transmission is enhanced as electromagnetic waves penetrate the STO layer, as shown in figure 8.

Finally, the transmission spectrum of the same samples is measured during the cooling process, as shown in figure 10. In experiments, the initial temperature is $T = 380$ K, which should be higher than the maximum temperature point in figure 8. Three temperature points are selected: 360 K, 330 K and 300 K. The average transmittance and bandwidth in figure 10 are consist with that in figure 8, which indicates that the temperature adjustability of samples is reversible. In order to more accurately explain the reversibility of the heating process and cooling process, figure 11. Gives the statistical results of figures 8 and 10. It is found that the statistical results show that the errors of the heating process and the cooling process are very low, which basically does not affect the validity of the measurement results.
4. Conclusion

In summary, a high transmittance broadband metasurface with Si layer and STO layer is verified in 100–130 THz. The effect of structural parameters on this transmission band is measured. Measured results indicate that this metasurface is insensitive to period \( P \), but the average transmittance and bandwidth are strengthened as the diameter \( D \) increases. Finally, transmission properties of this metasurface are modulated during heating and cooling, which reveals that this metasurface can be applied in temperature sensing.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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