# The wide-angle perfect absorption based on the optical Tamm states*

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(Received 29 April 2014)



Based on the optical Tamm states (OTSs), a metal-distributed Bragg reflector (DBR) structure is presented. The existence of optical Tamm states is demonstrated by the dip of reflectivity spectrum in photonic band gap. The properties of the optical Tamm states are investigated by applying the transfer matrix method. The effects of different metal thicknesses and angles on the absorption are studied by numerical simulation. The wide-angle perfect absorption appears when the metal thickness is 39 nm.

**Document code:** A **Article ID:** 1673-1905(2014)04-0317-4

**DOI** 10.1007/s11801-014-4070-2

Since the first perfect absorber composed of metallic split ring resonators and cutting wires was demonstrated by Landy et al[1], the research of this topic has grown rapidly due to its ability to absorb incident waves with near-unity absorption[2-8]. Perfect absorbers have potential in many applications, including selective thermal emitters[5], high efficiency solar cells[6], photodectors[7], plasmonic sensors[8], and so on.

Optical Tamm state (OTS) was first proposed by A. V. Kavokin[9]. Tamm state is a kind of surface state of localized electronics in solid-state physics, while the OTS is a kind of new interface mode. The electromagnetic field associated with OTSs is localized at the interface between two different media, and the intensity becomes weaker as the distance between them is bigger. In contrast to conventional surface states, OTSs can be directly excited in both TE and TM polarizations, even at normal incidence, especially in the metal-distributed Bragg reflector (DBR) interface. Compared with surface plasmon polariton (SPP), although they are both optical localization, the dispersion characteristic of OTSs is different. For instance, the dispersion of OTSs is parabolic with an effective mass at the order of $10^{-5}$ of a free electron mass[10]. OTSs are usually associated with a sharp reflection dip in the photonic band gap region, and the value of the full width at half maximum (FWHM) of the reflection dip is small. These characteristics of OTSs can be used for the design of resonant optical filters and highly sensitive sensor. Besides, the potential applications of OTSs have been proposed in polariton lasers, optical switch, enhanced Faraday rotation and the nonlinearity effects[11,12].

Gong et al[13] researched a two-dimensional plasmonic metal-dielectric-metal waveguide with a thin metallic layer and a dielectric photonic crystal in the core, which leads to near-unity absorption. In this paper, a metal-DBR structure is presented based on OTSs, and the wide-angle perfect absorption appears through optimizing the structure.

As is shown in Fig.1, the DBR structure consists of two different periodical dielectric layers. The dielectrics A and B are $SiO_2$ and $TiO_2$ with their refractive indices and thicknesses of $n_1$=1.47, $d_1$=255 nm and $n_2$=2.37, $d_2$=158 nm, respectively. The number of the periods is 15. The metal is chosen as Ag whose permittivity can be characterized by the Drude model as

$$\varepsilon = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + \mathrm{i}\nu)}, \quad (1)$$

where $\varepsilon_\infty$=3.7 represents the permittivity at infinite angular frequency, $\omega_p$ stands for the bulk plasma frequency with $\hbar\omega_p = 9$ eV, and $\nu$ means the electron collision frequency with $\hbar\nu = 0.018$ eV, according to Ref.[14]. The expression coincides well with the experimental result in the wavelength range from 400 nm to 2 000 nm. There is a cover layer D ($TiO_2$) between the metal and DBR, which has great effect on the OTSs[15].

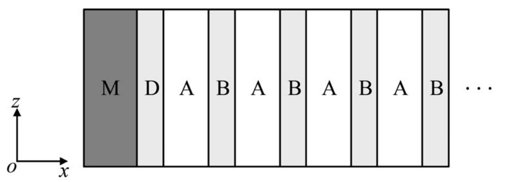


**Fig.1 Schematic diagram of the metal-DBR structure**

* This work has been supported by the National Natural Science Foundation of China (No.61107055).

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According to the mode eigen equation of the surface mode in Ref.[10], the dispersion curves of OTSs are shown in Fig.2. In our simulation, we choose the refractive index of the cover layer as $n_D$=2.37, and the thickness is 100 nm. The horizontal axis represents the tangential component $k_z$ of OTSs wave vector along the interface. Fig.2 also shows the stop band regime of the semi-infinite periodical photonic crystal (DBR). It is observed that the eigen-wavelength of OTSs is located in the stop band of the DBR, thus the electromagnetic field can attenuate evanescently in the DBR. We also find that although the wave vector component $k_z$ of the electromagnetic wave is less than the vacuum wave vector $\omega/c$, for example, $k_z$ is close to 0, the OTSs can be excited as well, that is to say the surface mode can be excited by the structure without the special assistant prism.

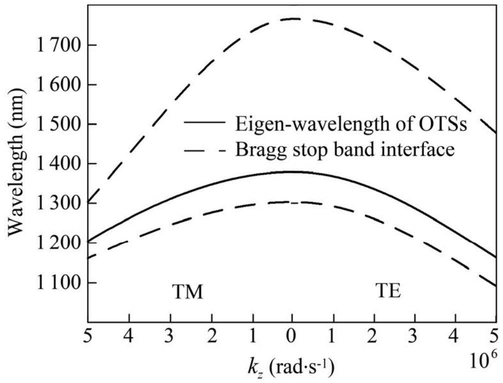



**Fig.2 The dispersion curves of OTSs on the interface between metal and DBR**

The eigen-wavelength of OTSs in the metal-DBR structure can be investigated by using the transfer matrix method[10]. When the energy of the incident electromagnetic wave can just excite OTSs in the structure, the reflectance $R$ of the incident electromagnetic wave drops deeply due to the strong coupling, and as a result, the minimum dip happens in the reflection spectrum. Fig.3 depicts the reflection spectrum at normal incidence, and the thickness of Ag is chosen as 40 nm. As shown in Fig.3, there is a deep dip centered at 1 380 nm in the reflection spectrum, which is associated with the eigen-wavelength of OTSs, and it is corresponding to the dispersion curve in Fig.2. The inset of Fig.3 demonstrates the vertical electromagnetic field inside the structure. We can clearly see that as a new surface mode, the energy of the electromagnetic field mainly localizes in the interface between the metal and DBR.

The penetrating power of the OTSs in the interface between the metal and DBR will be different when the Ag thickness changes, so the thickness affects the eigen-wavelength of the OTSs. Meanwhile, the incident electromagnetic wave can be absorbed to a certain extent due to the damping dissipation. The effects of the Ag thickness on the absorbance of the normal incidence electromagnetic wave and the eigen-wavelength of the OTSs are shown in Fig.4. As is shown in Fig.4(a), the Ag thickness is chosen as 30 nm, 40 nm, 50 nm and 60 nm respectively, and other parameters remain the same. As the Ag thickness increases, the absorption peak moves to the left, i.e., the corresponding wavelength decreases. The results show that the position of the absorption peak corresponds to the position of the reflection dip, which is due to the fact that absorbance $A$, reflectance $R$ and transmittance $T$ satisfy the conservation of energy $A+R+T=1$ and the transmittance $T$ is close to 0. When the Ag thickness is 40 nm, the absorbance can reach the maximum value 1, i.e., the perfect absorber appears, and at this time the eigen-wavelength of the OTSs is 1 380 nm. In Fig.4(b), we can clearly see the stereogram about the effects of the Ag thickness on the absorption and wavelength. As the penetration depth of the electromagnetic wave in the Ag layer is about 30 nm, if the Ag thickness is too small, the effects of the dielectric outside the metal on the surface states are intensified, which results in the big change of the eigen-wavelength of the OTSs. However, as the Ag thickness is bigger than 50 nm, the effects become smaller, and finally the eigen-wavelength of the OTSs tends to be 1 376 nm. The above results show that the perfect absorber appears when the Ag thickness is about 40 nm, and at this time, the intensity of the OTSs excited by the incident electromagnetic wave is the strongest, resulting in the biggest absorbance and zero reflection.

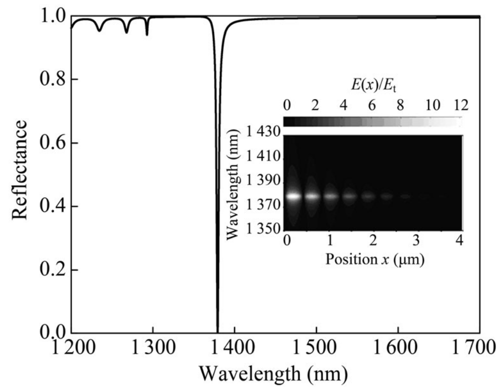
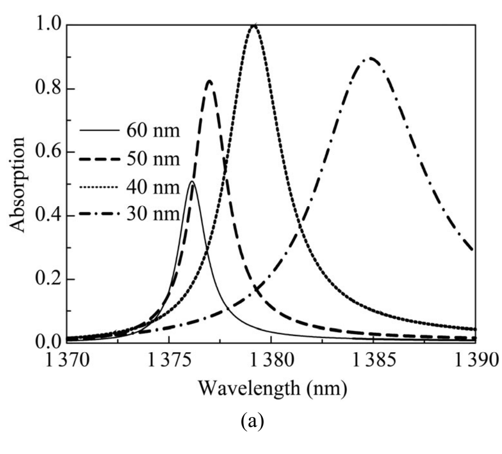
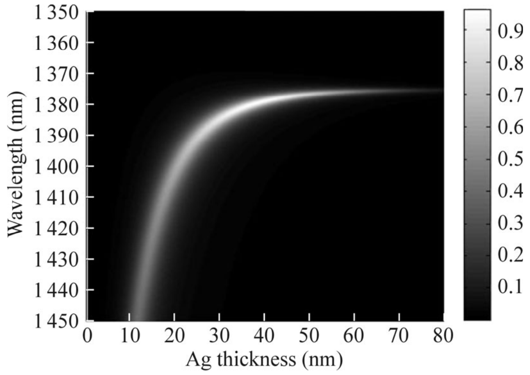



**Fig.3 The reflection spectrum at normal incidence**

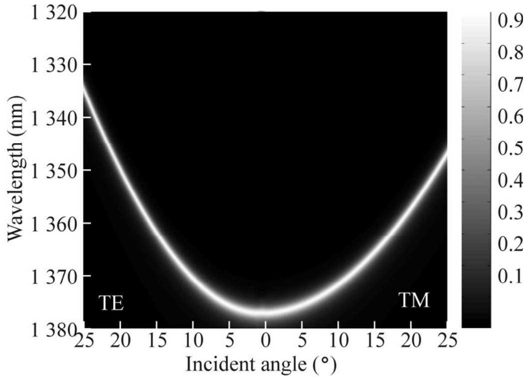




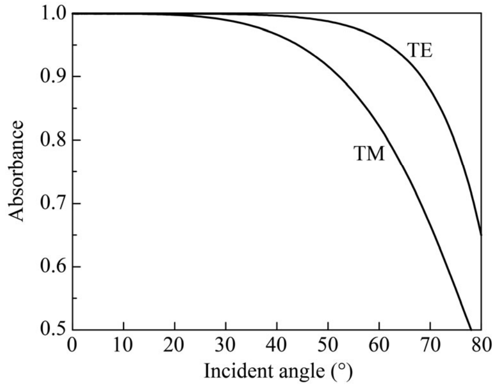

(b)

**Fig.4 The effects of the Ag thickness on the (a) absorption and (b) wavelength**

Studies show that at normal incidence, to make the perfect absorber appear, the most appropriate Ag thickness is 39 nm, and the electron collision frequency is $\hbar\nu = 0.018$ eV. Then we keep the Ag thickness as 39 nm and other parameters unchanged, Fig.5 shows the effects of the angle variation on absorption. As the stereogram shown in Fig.5(a), we can find that as the angle increases, the eigen-wavelength of the OTSs decreases, but the absorbance keeps more than 0.99, which is the so-called perfect absorber. Furthermore, Fig.5(b) shows the effect of polarization on the absorbance which can stay above 0.90 when the incident angle is less than 68° in TE polarization or 53° in TM polarization.




(a)




(b)

**Fig.5 The effects of angle variation on (a) wavelength and (b) absorption**

The effect factors on the perfection absorber in metal-DBR structure are not just the Ag thickness, but also the electron collision frequency. Fig.6 shows the change curve of the most appropriate Ag thickness corresponding to different electron collision frequencies when the perfect absorber can happen. For realizing the perfect absorber, the Ag thickness should be enlarged to enhance the absorption ability when the electron collision frequency is smaller.

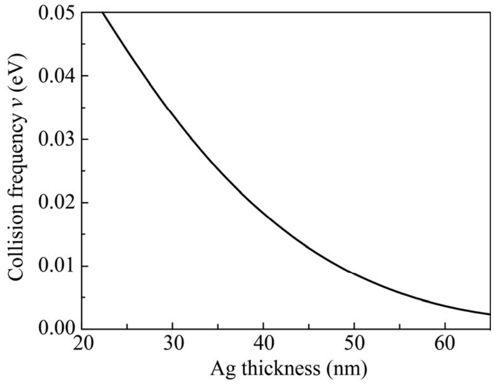



**Fig.6 The relationship between electron collision frequency and Ag thickness**

In summary, based on OTSs, we design a metal-DBR structure. The dispersion curves of OTSs are studied. There are two polarization modes which can be directly excited by ordinary polarized light in this structure. The best condition to realize the perfect absorber is investigated when Ag thickness changes. The wide-angle perfect absorption appears in the metal-DBR structure under certain conditions.

## References


[1] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith and W. J. Padilla, Physical Review Letters **100**, 207402 (2008).

[2] S. Chen, H. Cheng, H. Yang, J. Li, X. Duan, C. Gu and J. Tian, Applied Physics Letters **99**, 253104 (2011).

[3] X. Shen, Y. Yang, Y. Zang, J. Gu, J. Han,W. Zhang and T. J. Cui, Applied Physics Letters **101**, 154102 (2012).

[4] L. Huang, D. R. Chowdhury, S. Ramani, M. T. Reiten, S. N. Luo, A. K. Azad, A. J. Taylor and H. T. Chen, Applied Physics Letters **101**, 101102 (2012).

[5] X. L. Liu, T. Tyler, T. Starr, A. F. Starr, N. M. Jokerst and W. J. Padilla, Physical Review Letters **107**, 045901 (2011).

[6] J. Hao, L. Zhou and M. Qiu, Physical Review B **83**, 165107 (2011).

[7] Z. Liu, P. Zhan, J. Chen, C. Tang, Z. Yan, Z. Chen and Z. Wang, Optics Express **21**, 3021 (2013).

[8] N. Liu, M. Mesch, T. Weiss, M. Hentschel and H. Giessen, Nano Letters **10**, 2342 (2010).

[9] A. V. Kavokin, I. A. Shelykh and G. Malpuech, Physical Review B **72**, 233102 (2005).

[10] M. Kaliteevski, I. Iorsh, S. Brand, R. A. Abram, J. M. Chamberlain, A. V. Kavokin and I. A. Shelykh, Physical Review B **76**, 165415 (2007).
[11] C. E. Little, R. Anufriev, I. Iorsh, M. A. Kaliteevski, R. A. Abram and S. Brand, Physical Review B **86**, 235425 (2012).
[12] W. L. Zhang and Y. J. Rao, Chinese Physics B **21**, 057107 (2012).
[13] Y. Gong, X. Liu, H. Lu, L. Wang and G. Wang, Optics Express **19**,18393 (2011).
[14] J. Park, H. Kwi and B. Lee, Optics Express **16**, 413 (2008).
[15] H. Zhou, G. Yang, K. Wang, H. Long and P. Lu, Optics Letters **35**, 4112 (2010).