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Sub-nanometer linewidth perfect absorption in visible band induced by Bloch surface wave

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ABSTRACT

We demonstrate the unity absorption of visible light with an ultra-narrow 0.1 nm linewidth. It arises from the Bloch surface wave resonance in alternating TiO_2/SiO_2 multilayers. The total absorption and narrow linewidth are explained from the radiative and absorptive damping, which are quantitatively determined by the temporal coupled mode theory. When a silver film with proper thickness is added to the absorber, the perfect absorption is achieved with only 3 structural bilayers, in contrast with 8 bilayers required without Ag. Furthermore, significant field enhancement and an ultrahigh 2600/RIU sensing figure-of-merit are simultaneously obtained at resonance, which might facilitate applications in nonlinear optical devices and high resolution refractive index sensing.

1. Introduction

Perfect electromagnetic absorption with narrow bandwidth has intrigued extensive research due to its highly desirable performances in thermal emission [1,2] and optical sensing [3–5]. Metamaterial-inspired absorbers are intensively investigated thanks to their merits of complete absorption, compact structures and agile tuning of absorption wavelength. Compared with the wideband absorption which can be realized using various configurations such as the hyperbolic metamaterials [6,7] and multilayered film structures [8–10], squeezing the absorption linewidth to the nanometer level is rather more challenging because of the large radiation and absorption losses especially in the visible band. Several narrow band absorbers have been proposed based on the plasmon resonance in the metal-insulator-metal cavity [3], nanoslit microcavity [4], lattice resonance metal surface [11,12], gap coupled nanopillars [13] and plasmon-optical cavity coupling [14,15]. Nonetheless the obtained absorption linewidth is generally broader than 10 nm and the corresponding quality factor is below 200. The linewidth can be further reduced to ~1 nm using the cascaded Fabry-Perot cavity [16], the lamellar grating [5,17] and the guide mode resonance structure [18,19]. Yet the complex structured surface of grating poses great challenges to microfabrication. Recently, it is demonstrated that ultra-narrow resonance is achieved in the dielectric photonic crystal (PhC) arising from the Bloch surface wave (BSW) resonance [20–23]. It circumvents the linewidth broadening caused by the large metal dissipation. Additionally, the radiation loss can be very low when the PhC is composed of a large number of stack layers.

In this work, complete light absorption with the extreme 0.1 nm bandwidth and high quality factor of 4980 is achieved in the visible band. It originates from the BSW resonance in a one-dimensional dielectric PhC terminated by a silver (Ag) film. Compared with the conventional all-dielectric structure, the introduction of the silver film effectively reduces the required layer number in PhC to achieve perfect absorption. The absorption and linewidth of BSW resonance are analyzed using the temporal coupled mode theory in terms of the relationship between radiative and absorptive decay rates. It reveals that the reduction of radiative damping caused by the Ag film accounts for the complete absorption with fewer PhC layers. Moreover, great electric field enhancement is produced near the structure surface, which together with the narrow absorption bandwidth, enables refractive index sensing with ultrahigh figure-of-merit.

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2. Structures and calculation model

The schematic of the absorber is shown in Fig. 1. The structure is in sequence composed of a silica cover layer, a dielectric PhC and a thin silver film on the silica substrate. The PhC includes N repetition periods of alternating Titanium Dioxide/silica (TiO_2/SiO_2) bilayers. The whole structure can be readily fabricated using the thermal evaporation process or magnetron sputtering. The BSW resonance is induced from an obliquely illuminated transverse electric (TE) planar wave (E//Y) with an incident angle θ_{inc}. Because the BSW resonance is non-radiative [20,21], it cannot be directly excited by the far field radiation. Therefore the evanescent coupling via a BK7 prism is employed with θ_{inc} being larger than the critic angle θ_{cri}. In the calculation, BK7 glass and SiO_2 are assumed to have the same lossless refractive index of 1.431. TiO_2 has the refractive index of 2.123 + 0.0001j to account for the tiny intrinsic material dissipation. The corresponding thickness in a unit cell is $h_{TiO2} = 105$ nm, $h_{SiO2} = 155$ nm, period $\Lambda = h_{TiO2} + h_{SiO2}$, and the covering SiO_2 layer is $h_{top} = 40$ nm thick. Using the transfer matrix method (TMM) [24,25], the reflection (R) and transmission (T) are calculated based on the following matrix formulation. For the system containing $m+2$ dielectric layers (including the semi-infinite substrate and covering layer), the total transmission matrix M is modeled as $M = M_1 \cdot M_2 \cdot \ \ldots \ \cdot M_m \cdot M_{m+1}$, where the matrix M_i is expressed as

$$M_i = \frac{1}{t_{i,i+1}} \begin{bmatrix} 1 & r_{i,i+1} \\ r_{i,i+1} & 1 \end{bmatrix} \times \begin{bmatrix} e^{-j\delta_{i+1}} & 0 \\ 0 & e^{j\delta_{i+1}} \end{bmatrix} \quad (1)$$

The transmission phase shift is $\delta_i = 2\pi n_i h_i \cos(\theta_i)/\lambda$, which is determined by the incident wavelength λ, layer thickness h_i, refractive index n_i and refraction angle θ_i in every structural layer. The refraction angle is governed by the Snell's law $n_i \sin(\theta_i) = n_1 \sin(\theta_{inc})$. The Fresnel reflection coefficient $r_{i,i+1}$ and transmission coefficient $t_{i,i+1}$ for TE polarization are given as Eq. (2) and Eq. (3), respectively. The reflection (R) and transmission (T) are computed as $R = |M_{21}|^2/|M_{11}|^2$ and $T = n_{m+1}\cos(\theta_{m+1})/(n_1\cos(\theta_{inc})|M_{11}|^2)$ [24,25]. Then the absorption is obtained as $A = 1\text{-}R\text{-}T$.

$$r_{i,i+1} = \frac{n_{i+1}\cos(\theta_i) - n_i\cos(\theta_{i+1})}{n_{i+1}\cos(\theta_i) + n_i\cos(\theta_{i+1})} \quad (2)$$

$$t_{i,i+1} = \frac{2n_i\cos(\theta_i)}{n_{i+1}\cos(\theta_i) + n_i\cos(\theta_{i+1})} \quad (3)$$

3. Results and discussion

For clarity of analysis we start from the absorber without including the silver layer. The photonic bands of the 6-bilayer structure are shown in Fig. 1(b), where the transmission and forbidden bands are represented by the blue and white areas, respectively. The dispersion curve of BSW mode emerges in the forbidden band beyond the air light cone. It means that the BSW cannot couple to the free space light due to the wavevector (β) mismatch. Therefore, the scheme of totally internal reflection (TIR) in a high index prism is used to compensate for the additional wavevector. The absorption under prism excitation is shown in

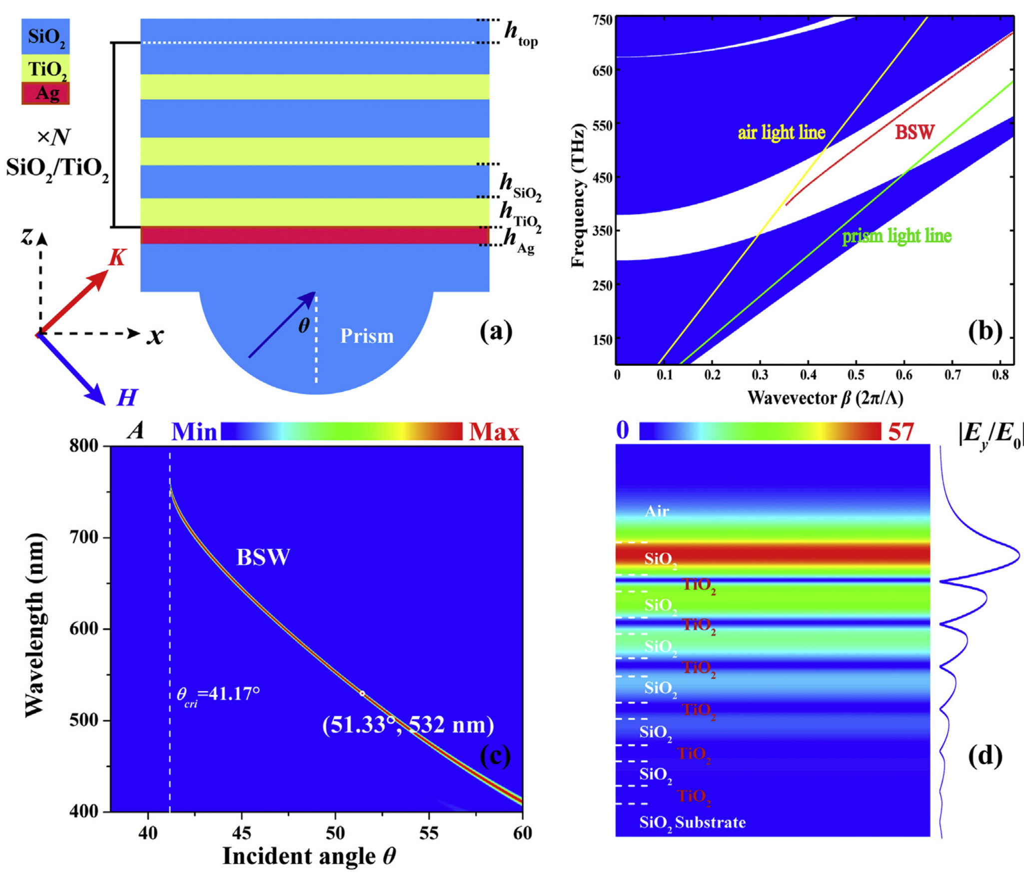

Fig. 1. (a) Schematic of the absorber with N periodic TiO_2/SiO_2 bilayers. (b) The band diagram of the PhC with 6 bilayers. The dispersion of BSW mode is indicated by the red line. (c) Absorption of the $N = 6$ structure varying with the incident angle and wavelength. The white dot denotes the BSW absorption at 532 nm. (d) Spatial distribution of normalized electric field at 532 nm BSW resonance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)