

Robust absorption broadband in one-dimensional metallic-dielectric quasi-periodic structure

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Abstract: We demonstrated that a broad and robust absorption band for a wide range of incidence angles and for both polarizations can be realized using a one-dimensional metallic-dielectric quasi-periodic structure, when the thickness of the constituent metal is comparable to its skin depth. The absorptance in such peculiar structure can exceed 99% to meet different applications. Furthermore, employing the effective medium approach, a theoretical expression has been deduced to instruct the working frequency of the absorption band. By tuning the permittivity and thickness of the constituent layers, the robust absorption band can cover the wavelength from the visible to the near-infrared.

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1. Introduction

Since 1987, it has been suggested that [1] photonic density of state in a photonic band gap (PBG) regime vanishes and no electromagnetic (EM) wave is allowed to penetrate into the photonic crystal structure. Therefore, spontaneous emission, as well as optical absorption, is suppressed even in the lossy material. However, the photonic density of state is significantly increased [2] near the band edge. As a result, it enables to enhance the interaction between light and matter substantially.

Based on this unique property, optical absorption enhancement [3-10] has recently become an active subject and attracted much attention. The intriguing experiments by Lin *et.al.* [5,6] worked out highly optical absorption peak, as well as high efficient light emission by applying a voltage, in a tungsten three-dimensional photonic crystal having a diamond symmetry when the EM wave propagates along the $\langle 001 \rangle$ direction. They found that the enhancement is due to three criteria: the slow group velocity of EM wave, a long photon-matter interaction length and the material's intrinsic absorption. Later on, optical absorption enhancement has been theoretically realized in TE-polarized wave of two-dimensional square metallic photonic crystal [7], as well as the one-dimensional (1D) period structure when the light propagates for the normal incidence [8].

For many practical applications, the broad efficient absorption band regardless of incident angles and polarizations is always necessary. However, structure with broad efficient absorption band not only for both polarizations but also for the wide incidence angle has not been reported. Therefore, to investigate the structures with broad efficient absorption band for both polarizations and with wide incidence angle are in urgent need.

In this work, we demonstrate that a class of 1D metallic-dielectric quasi-periodic structure (MDQPS) that possesses the broad and efficient absorption band for the wide incidence angle and both polarizations. The high efficient absorption bands of such simple 1D system covering from the visible to the near-infrared are designed.

2. Fibonacci photonic crystal and conditions of high absorption band

It is shown that [11,12] all-dielectric Fibonacci quasi-periodic structures have peculiar photonic band structure. The number of PBGs becomes more than the rigorously period structure in a given frequency range. That is to say, the slope of photonic band, which stands for the group velocity in 1D case, may vanish. As a result, the photonic density of state (i.e. the reciprocal of the group velocity) can be higher than the rigorously period PC. In addition, if the constituent material of period structure is lossy, e.g. metals, optical absorption may be efficiently enhanced within the frequency range of photonic band. However, since the EM wave is evanescent in the bulk metal, it experience high reflective in the visible and the near-infrared regions as the thickness of metal film is far beyond its relevant skin depth. On the other hand, if the thickness of metal film is comparable to its skin depth, the EM wave can experience less reflectance backwards and more transmittance forwards. If the excitation conditions are suitably chosen, a 1D metal-dielectric nanofilm structure can exhibit unit transmission due to surface-plasmon-enhanced resonant tunneling [13]. Consequently, employing the MDQPS structure with thin metal film, the interactions between light and matter become longer. Therefore, it is reasonable to predict that the quasi-periodic structure composed of thin metallic and dielectric layers can be viewed as a potential candidate for highly efficient optical absorption.

The Fibonacci sequence, known as a common quasi-periodic structure, can be generated by a recursive relation: $S_{j+1} = \{S_{j-1}, S_j\}$, $j \geq 1$, where S_j is the j th order sequence. For example, the unit cells of the first three order sequences are $S_2 = MD$, $S_3 = DMD$, $S_4 = MDDMD$, where $S_0 = M$, $S_1 = D$, and M , D represent the thin metal and dielectric layer, respectively. By employing the transfer matrix method [14], the calculated band structures of the first three order Fibonacci MDQPS are shown in Fig. 1. As a numerical example, the refractive index and thickness of the dielectric layer are 1.38 and 180 nm, while the metal is 10nm-thick tungsten for all the Fibonacci MDQPS. The permittivity of tungsten is taken from Palik [15],

Insets in Fig. 1 are the unit cells of the corresponding order Fibonacci MDQPS. It is found that a cutoff frequency exists in all the Fibonacci MDQPS due to the Bragg scattering, which is similar to the rigorously period structure. Second, more PBGs appears in the higher order Fibonacci MDQPS, e.g. the S_4 structure, than the lower order ones, e.g. the S_3 structure, because the former is more difficult to satisfy the Bloch wave condition [14] as its disorder increases. Third, as expected, the slope of photonic band decreases in the higher order Fibonacci MDQPS than the lower order ones between the cut-off frequency and near $1.8\mu\text{m}^{-1}$.

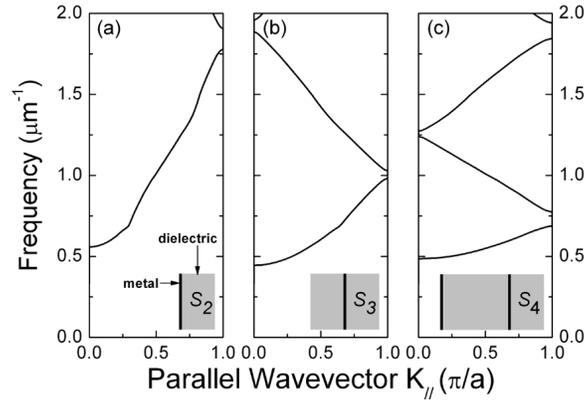


Fig. 1. Photonic band structure of the (a) S_2 (period), (b) S_3 and (c) S_4 structure, respectively. The real part of permittivity of tungsten and the low refractive index 1.38 of the dielectric layer are taken for calculation. The thicknesses of the metal and dielectric layers are taken to be 10 and 180 nm, respectively. Insets are the schematics of the unit cells of three corresponding Fibonacci MDQPS. The black regions represent the thin metallic layers while the gray regions represent the dielectric layers. The abscissa is in unit of π/a , where a is the lattice constant of an unit cell. $K_{||}$ means the component of wavevector paralleled to the interfaces.

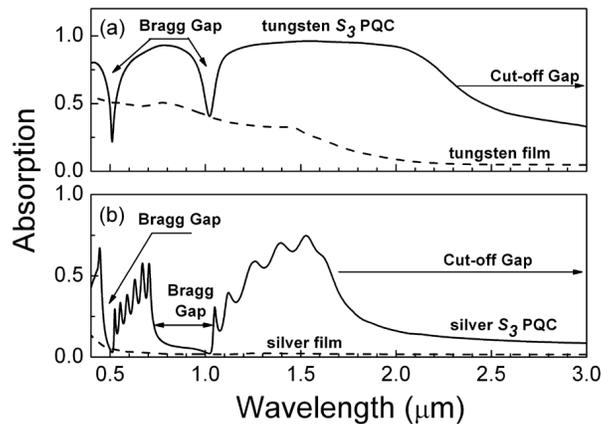


Fig. 2. Calculated absorption spectra (solid lines) for the S_3 structures with 7 periods. The constituent metal is tungsten (a) and silver (b) respectively. The other parameters of the structures are the same as Fig. 1. The absorption spectra of a uniform tungsten (a) and silver (b) slab with a thickness equal to 100 nm (dashed lines) is shown as a reference.

Figure 2 shows the absorption spectra of S_3 with seven periods. The parameters are the same as before. In Fig. 2(a), it can be seen that an absorption broadband (solid line) in the tungsten MDQPS is achieved from 1.17 to $2.05\mu\text{m}$, which is corresponding to the first photonic band shown in Fig. 1(b). Obviously, it is significantly stronger than the 100nm-thick tungsten film (dashed line). Note that the skin depth is about 20~30nm in the studied

wavelength. Absorbance decays gradually in the long wavelength limit because no propagating mode is allowed below the cutoff frequency in the MDQPS. Moreover, the reflectance of S_3 increases substantially within the PBG range due to Bragg scattering. This causes the dips in the absorption spectrum around 1.02 and 0.5 μm . Similar behavior of the silver MDQPS structure is shown in Fig. 2(b). The distinct absorption enhancement occurs both in the visible and the near-infrared regions as compared to the 100nm-thick silver film.

Another consideration to achieve robust absorption band is the constituent metal. It has been shown that the peak of absorption enhancement originates from the intrinsic metallic absorption. However, to achieve absorption enhancement band, it should be more important to satisfy the impedance matching condition on the interface of two materials. The EM wave, thereby, can penetrate into the structure more deeply and the energy may be absorbed completely. The simulation results are shown in Fig. 2. Obviously, the tungsten MDQPS exhibits the absorption band while the silver MDQPS structure exhibits the absorption peak. This is because the impedance matching in the tungsten case is better than that in the silver case, and the imaginary part of permittivity of tungsten is much larger than silver within the studied frequency range.

3. Simulation results

Figure 3 shows the absorption spectra of different order Fibonacci MDQPS, S_2 , S_3 , S_5 ($DMDMDDMD$), and S_7 ($DMDMDDMDMDDMDDMDDMD$) with 10, 7, 3, and 1 period, respectively. The other parameters are the same as Fig. 1.

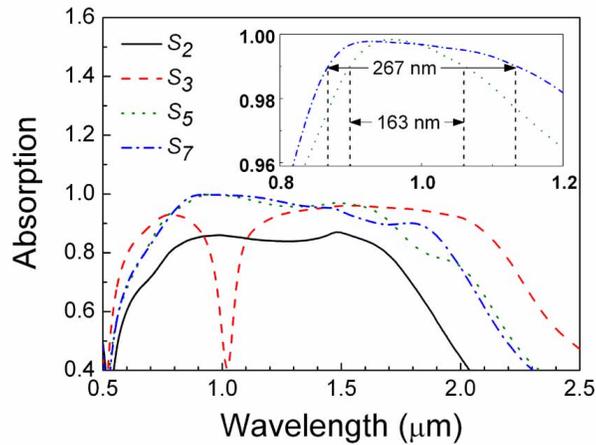


Fig. 3. (color online) Calculated absorption spectra for different order Fibonacci MDQPS with tungsten layer. The S_2 , S_3 , S_5 , and S_7 with period number 10, 7, 3 and 1 are shown by solid, dashed, dot and dashed-dot lines, respectively. The high absorption data above 96% is shown in the inset. The vertical dashed lines mark the wavelength range of the total absorption. The other parameters of the structures are the same as Fig. 1.

One can see that the high order Fibonacci MDQPS exhibits broad and robust absorption band although numbers of small PBGs exist in the studying frequency range. For example, the robust absorption band (above 90%) of S_5 and S_7 is 0.76 ~ 1.65 μm and 0.74 ~ 1.71 μm , respectively, which cover the whole near-infrared region. For high order MDQPS, the Bragg scattering becomes weaker because of the increasing disorder and the less periods. The reflectance within the PBG range for finite MDQPS is no longer strong although the PBG exists in the infinite MDQPS. Therefore, a broad and robust absorption band can be achieved. Furthermore, it is expected that both the width of the absorption band and the absorbance of the MDQPS are larger than the rigorously period structure, i.e. S_2 . Note that a high efficient absorption band (above 99%) is achieved in the S_5 and S_7 structures with the spectral bandwidth of 163 nm and 267 nm. By optimizing the practical design, one can obtain the best

bandwidth 182 nm and 314 nm in the S_5 and S_7 structures, when the thickness of the dielectric layer is 220 nm and 230 nm, respectively. A further calculation reveals that, for high order MDQPS with several periods, e.g. S_7 with 3 periods, the EM wave decays almost completely in the first period of the structure. In other words, the additional periods of the structure are insignificant on optical absorption enhancement.

The absorption band discussed above is mainly in the near-infrared region. In fact, it remains valid to be extended to the visible region by properly choosing the parameters of constituent materials. Since it is difficult to give a straightforward formulation rigorously in the higher order Fibonacci sequence, we restrict ourselves to the S_3 structure. For this particular case, the structure with the unit cell of S_3 can be regarded as an effective medium. Due to the mirror symmetry of the stack, the total transfer matrix of a unit cell can be written in the form of matrix of a single layer:

$$T_{DMD} = \begin{pmatrix} \cos \delta_{eff} & j \sin \delta_{eff} / \sqrt{\epsilon_{eff}} \\ -j \sqrt{\epsilon_{eff}} \sin \delta_{eff} & \cos \delta_{eff} \end{pmatrix} \quad (1)$$

where δ_{eff} is the effective phase thickness, and ϵ_{eff} is the effective permittivity, written as:

$$\epsilon_{eff} = n^2 \left[\frac{\sin 2\delta_d \cosh \delta_m - \frac{1}{2} \left(\frac{n_i + n}{n} \right) \sinh \delta_m - \frac{1}{2} \left(\frac{n_i - n}{n} \right) \cos 2\delta_d \sinh \delta_m}{\sin 2\delta_d \cosh \delta_m - \frac{1}{2} \left(\frac{n_i + n}{n} \right) \sinh \delta_m + \frac{1}{2} \left(\frac{n_i - n}{n} \right) \cos 2\delta_d \sinh \delta_m} \right] \quad (2)$$

where $\delta_d = (\omega/c)nd$ and $\delta_m = (\omega/c)n_i d_m$ are the phases of the dielectric and metallic layer, respectively. n and d are the refractive index and thickness of dielectric, n_i and d_m are the extinction coefficient and thickness of metal, and c is the speed of light, respectively. After some algebra calculation, Eq. (2) can be deduced using the effective medium approximation:

$$\epsilon_{eff} = n^2 \left[\frac{2\delta_d \cosh \delta_m - \frac{n_i}{n} \sinh \delta_m}{2\delta_d \cosh \delta_m + \frac{n}{n_i} \sinh \delta_m} \right] \quad (3)$$

and finally written in the Drude model form:

$$\epsilon_{eff} = \epsilon_0^{eff} \left(1 - \frac{\omega_p^{eff 2}}{\omega^2} \right) \quad (4)$$

where ω_p^{eff} and ϵ_0^{eff} are the effective plasma frequency and effective static permittivity of the 1D MDQPS, given by:

$$\omega_p^{eff 2} = \frac{c \tanh \delta_m}{2\epsilon_0 d} \omega_p \quad (5)$$

and

$$\epsilon_0^{eff} = \frac{2\epsilon_0 \omega_p d}{2\omega_p d + c \tanh \delta_m} \quad (6)$$

Here, $\epsilon_0 = n^2$ and $\delta_m \sim \omega_p d_m / c$ in the long wavelength approximation, where ω_p is the plasma frequency of metal. It can be seen from Eq. (5) that the photonic band, as well as the absorption band, can be tuned to the higher frequency range using metal with higher plasma frequency or thin dielectric with lower refractive index. It should be noted that the thickness of the metal thin film should be comparable to its skin depth for the absorption enhancement. Similar guideline is valid in the higher order Fibonacci MDQPS by numerical

simulation. For example, if the thickness of tungsten and dielectric layer of S_5 is 10 nm and 120nm, the broad absorption band above 90% is from 0.544 to 1.514 μm , which covers the whole region from the visible to the near-infrared. Furthermore, similar robust absorption enhancement can also be achieved in other quasi-periodic structure. Take the fifth order Thue-Morse sequence for example. We indeed find out the absorption band exceeding 97% from 0.92 to 1.26 μm when the refractive index of dielectric, the thicknesses of dielectric and tungsten layer are 2.67, 80nm and 20nm, respectively.

4. Absorption broadband for oblique incidence

The absorption efficiencies of two polarizations should be considered not only for the normal incidence, but also for the oblique incidence in the 1D structure. In fact, the high efficient absorption band of the Fibonacci MDQPS can be maintained in a wide incidence angle. For example, Fig. 4 shows the absorption band above 90% of S_5 for both polarizations as a function of incidence angle. It is noted that the absorptance of both polarizations is above 90% over the wavelength range about 0.8 ~ 1.6 μm for $0^\circ \sim 50^\circ$. In other words, the band edge is nearly unchanged within a wide range of the incidence angle. For larger incidence angles the lower absorptance is due to the impedance mismatch which is similar to the 2D case [7].

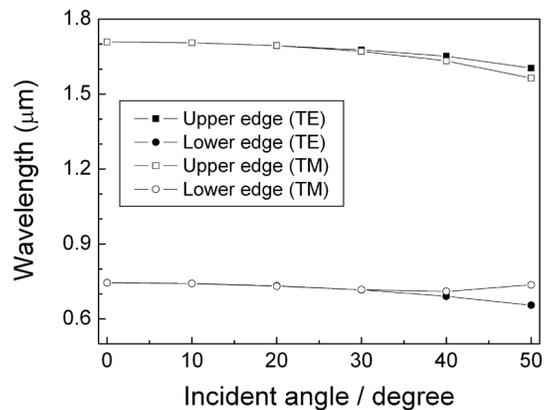


Fig. 4. The angle-dependent absorption band (above 90%) of the S_5 structure with tungsten metallic layer for both polarizations. The solid and hollow symbols represent the TE and TM polarization, respectively. The square and circle symbols represent the upper and lower edge of the strong absorption band. The other parameters of the structures are the same as Fig. 1.

5. Summary

In summary, we have proposed a class of 1D Fibonacci MDQPS structure that exhibits a broad and robust absorption band. The absorption enhancement is attributed to the slower group velocity of EM wave in quasi-periodic structure as compared to the rigorously period structure, the impedance matching and the high intrinsic absorption of consistent materials. We have demonstrated that the highly efficient absorption band can reach more than 99% in the high order Fibonacci structure. The spectral bandwidth of S_7 is over 300nm in the near-infrared region. Moreover, we have found that the robust absorption broadband (above 90%) is almost independent within a wide range of incidence angles for both polarizations. By the optimization of the geometric thickness of the simple 1D multilayer structure, the absorption band can be tuned to cover the wavelength from the visible to the near-infrared. Our structures may have wide applications in thermal emission, incandescent light and martial concealment technology because of its peculiar properties, easy fabrication and small size.

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