Robust Absorption in a Four-Layer Dielectric-Metal Structure

J. W. Dong, K. S. Wu, S. J. Jiang, and H. Z. Wang

***Abstract*—This letter predicts that robust absorption will appear in a four-layer dielectric-metal structure, and our experimental results verify this prediction well. The mechanisms are as follows: 1) The four layers form a cavity, and zero phase shift at the interface between the first metallic layer and the second dielectric layer is designed to make the backward light form a destructive interference and minimize the reflection. 2) The slow-light effect near the cutoff frequency in this structure increases the absorptive length many times. 3) It also can be explained as an asymmetric resonator, which satisfies the critical coupling condition. Many applications can be developed from this work, such as ensuring laser welding high quality for infrared transparent optoelectronic components.**

***Index Terms*—Absorption, dielectric-metal structure, laser welding, multilayer, optoelectronic components.**

I. INTRODUCTION

Since the initial prediction of Yablonovitch and John [1], [2], photonic crystals (PCs) have attracted extensive studies due to their unique properties and potential applications. In the photonic band gap, the electromagnetic (EM) waves cannot transmit [1] and the photonic density of state equals to zero. Therefore, both emission and absorption are suppressed. Nevertheless, near the band edge, the group velocity decreases [3], i.e., light slows down in these frequencies. As a result, the light–matter interaction will be enhanced, which results in optical absorption enhancement and makes the optical absorption enhancement in metallic-dielectric (MD) structures become an important subject [4]–[8]. Many potential applications, such as thermal radiation enhancement [9], are developed from this subject.

On the other hand, in the fabrication of optoelectronic devices, soldering techniques are necessary. Recently, 1.06-μm infrared lasers were used for welding the wafers, chips, optical wave guides, and other optical micro-components. It is well known that metal films always reflect light as in a mirror. In the infrared laser welding, metal films always reflect a majority of the input laser. People have to increase the input laser density. However, as the temperature of metal film approaches its melting point, the ratio of reflection/absorption suddenly decreases. It causes the metal film to absorb too much energy, which makes the welding fail. This problem restricts the development of precise laser welding in optoelectronic devices.

In this letter, we solve this problem. More than 99% of input laser energy can be absorbed in a four-layer MD thin film structure, and its mechanism is discussed in detail.

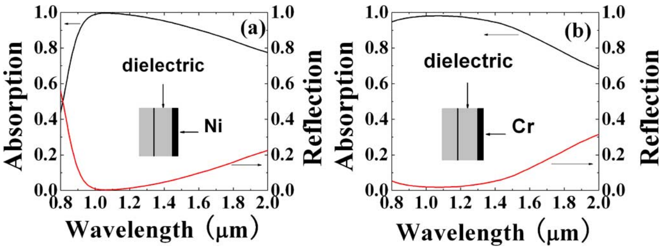

Fig. 1. Absorption/reflection spectra of the MD structures at normal incidence. The thicknesses of the dielectric and metallic layers are: (a) 200, 10, 253, 80 nm and (b) 160, 9, 120, 90 nm. The absorbance at 1.06 μm is (a) 99.6% and (b) 98.1%. Insets: sketches of the structures (gray/black region represents the dielectric/metallic layers).

II. ROBUST ABSORPTION IN DIELECTRIC-METAL STRUCTURE

Genetic algorithm (GA) is an optimization method, which is inspired from Darwinian evolution. Many important results are achieved by the use of this method [13].

In GA calculation, there are two steps. In the first step, we optimize the order of layers with the given thicknesses. The GA optimization is implemented by representing the materials of a four-layer structure as a binary string (0, 1 for dielectric and metallic layer, respectively). The GA results show that the dielectric incidence layer benefits the appearance of the robust absorption peaks, while the metallic incidence layer benefits the appearance of the low absorption peaks. In the second step, after the best order of materials (MD-MD) is obtained, we optimize the thickness of each layer. In this step, four eight-bit binary strings are used to represent the thicknesses within a given range. The fitness function of each possible solution in these two steps is given by the inverse of absorptance of the welding laser frequency (1.06 μm). The refractive index of the dielectric layer is 1.38 (MgF_2), and the permittivity of the metal (nickel and chromium) is taken from [14]. The simulation results show that many structural parameters satisfy the requirement of robust absorption. Fig. 1 shows two results as examples, in which high absorption appears at 1.06 μm for normal incidence.

The previous results are obtained at room temperature. As we know, the permittivity of metal changes with temperature. Firstly, the real part of permittivity decreases with temperature. It makes the impedance matching better and lets more waves

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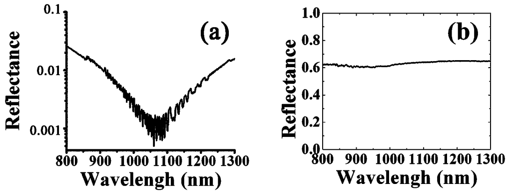

Fig. 2. Experimental results: (a) Reflectance of $MgF_2 - Cr\text{-}MgF_2 - Cr$ structures at normal incidence. The structural parameters are the same as those in Fig. 1(b). (b) Reflectance of chromium slab with a thickness of 100 nm.

penetrate in metal. Secondly, the imaginary part of permittivity increases with temperature, so that the intrinsic absorption will be enhanced [15]. These relations between the permittivity and temperature will ensure the critical condition meet [5] and make the robust absorption exist in high temperature.

III. EXPERIMENT AND APPLICATIONS

Many potential applications can be developed from this robust absorption in MD structure, such as laser welding for infrared transparent optoelectronic components. It is well known that metal film reflects more than half of incident light, as shown in Fig. 2(b). So in welding, we have to increase the input laser energy to compensate the reflecting losing. As the temperature approaches the melting point of the metal, the absorbance of the metal will suddenly increase, which makes the metal absorb too much laser energy to boil out the metal. It makes the welding fail.

If this four-layer metallic-dielectric structure is used as welding material instead of a single metal film, the input laser energy will be totally absorbed. Therefore, the input laser energy can be exactly equal to the melting energy. This structure will make welding stable, reliable, and firm.

Our experimental result is demonstrated in Fig. 2(a). We use MgF_2 and Cr as dielectric and metallic layers, respectively. This four-layer structure is fabricated by vacuum coating. The reflectance is measured by using a spectrophotometer (Perkin Elmer, model Lambda-900). Fig. 2(a) demonstrates almost no 1.06 μm light is reflected from this structure; zero transmittance of this structure is measured. Therefore, the absorbance at 1.06 μm is higher than 99.9%. This is well consistent with the calculated result shown in Fig. 1(b). As a reference, we also measure the reflectance of a 100-nm-thick chromium slab, as shown in Fig. 2(b), which is the case of welding in common use. In addition, our calculation results demonstrate that low reflection $(< 5\%)$ at 1.06 μm appears within a large range of incidence angle (50°).

IV. DISCUSSION AND THEORETICAL ANALYSIS

In this section, the mechanism of this robust absorption in this four-layer MD structure will be demonstrated. As we know, in metal, there is a skin effect for EM propagation. For visible and the near-infrared light, the skin depth is thinner than 100 nm. For the bulk metal, the EM wave is an evanescent wave within metal, and thus high reflection appears. On the contrary, if the metal film is thinner than its skin depth, the optical tunneling occurs to make a majority of input EM wave transmit through the metal. Thus, the metal sandwiched between two dielectric layers should be designed thinner than its skin depth. This is consistent with our GA optimization. If the thickness of this metallic layer, together with the other layers of MD film, is suitably chosen, total input laser energy will transmit through the first metal film, and the reflected loss on the surface of metal will almost be equal to zero.

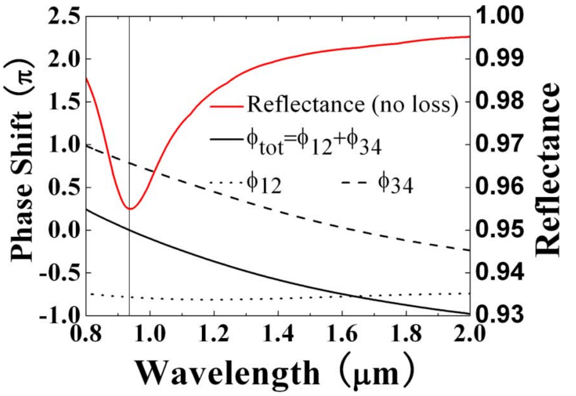

Fig. 3. The relationship between phase-shift and wavelength of the structure in Fig. 1(a). The dotted, dashed, and solid line represents the reflection phase shift of the first two layers, the last two layers, and the total phase shift, respectively. The red curve represents the reflection when the metal absorption is absent. The vertical thin solid line shows that the frequency of minimum reflection is just the frequency of zero total phase-shift.

Next, we turn to study the phase property in this simple four-layer structure. No reflected loss relates to the phase property of cavity. Here, the cavity refers to the interface between the first metallic layer and the second dielectric layer. Of course, we can also regard the dielectric layer between the metallic layers as the cavity. Both are equivalent and the results will be the same. Take the structure shown in Fig. 1(a) as an example. Fig. 3 shows the relationship between the reflection phase shift and the wavelength in a lossless model, i.e., let $\mathrm{Im}(\varepsilon_{\mathrm{metal}}) = 0$. It can be found that the reflection phase shift of the first two layers (ϕ_{12}) is much different from the last two layers (ϕ_{34}). At the wavelength of 936 nm, the total phase shift becomes zero, leading to a Fabry–Perot resonance. As a result, there is a minimum in the reflection spectrum in the lossless model. Once the realistic material parameter is considered, it is expected that such a Fabry–Perot resonance will not only increase the distance of interaction between the light and absorptive matter, but also let the multiple reflected EM waves almost destructed. Thus, zero reflection can be achieved. However, it should be noticed that the realistic material parameter is slightly larger than the lossless case. For example, the complex refracted index of nickel at 1.06 μm is $2.85 + 5.1i$ (with loss) and 4.23i (without loss), respectively. It follows that the resonant frequency in the lossless model is blue-shifted to the numerical and experimental results.

Except the zero phase shifts, there is another important effect in the structure. Similar to the 1-D PC with rigorous period, there is a cutoff frequency in this MD structure. Here, the meaning of "cutoff frequency" is that the system cannot transmit input signal whose frequency lies below this boundary frequency. Near this cutoff frequency, the group velocity decreases remarkably. It means that the slow-light effect appears. Such an effect will lengthen the absorptive distance, as well as the absorbance, which is proportional to the length of absorptive distance. To demonstrate the mechanisms described above,

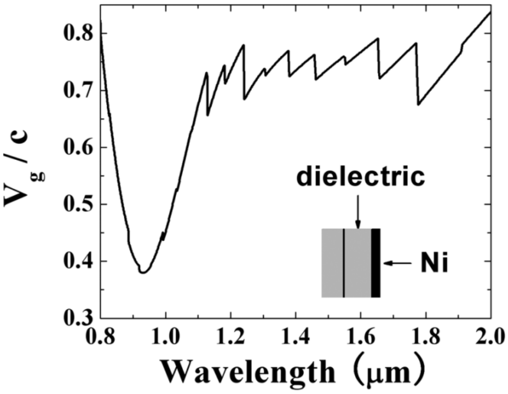

Fig. 4. The group velocity versus the wavelength. The structural parameters of the structure are the same as those in Fig. 1(a), except that the metal absorption is not considered, i.e., $Im(\varepsilon_{\mathrm{metal}}) = 0$.

we calculate the group velocity as a function of the wavelength in the lossless model. The complex transmission coefficient is obtained by the transfer matrix method [16]

$$t = \sqrt{T}\exp(i\phi) = x + iy$$

and the group velocity is

$$v_g = \frac{d\omega}{dk} = D\frac{x^2 + y^2}{y'x - x'y}$$

where D is the total length of the structure, and $x' = dx/d\omega$ and $y' = dy/d\omega$ [3]. It is shown in Fig. 4 that the group velocity significantly decreases at 936 nm due to the multiple scattering, which demonstrates that the slow-light effect appears in this finite MD structure. This is similar to the rigorously periodic PC structure [4]. Slow light is equivalent to the increase of the light–matter interaction time or distance. Therefore, as the metal absorption loss is considered, the slow-light effect will make the light be drastically absorbed. Note that the reasons for frequency differences between the lossless model and realistic system are the same as those mentioned in the previous paragraph.

Finally, we briefly explain the reason in the framework of resonator theory. The four-layer MD structure can be regarded as a resonator (the middle two layers) with two walls (the first and last layers). In the absence of losses, the reflection may vanish at the resonant frequency when the system possesses mirror symmetry. However, the reflection may also be equal to zero when the damping coefficient is equal to a certain critical value in spite of the mirror symmetry breakdown. In our structure, the right wall (the second metallic layer) is opaque with zero transmission coefficients, which implies the symmetry breakdown. Meanwhile, the left wall (the first dielectric layer) and the resonator provide the transmission coefficient and the damping coefficient, respectively. The coefficients are equivalent to each other. It leads to the critical coupling meeting. Therefore, the zero reflection and the total absorption can be reached at the resonant frequency [5], [17], [18].

V. CONCLUSION

In summary, a robust absorption is obtained in a four-layer MD structure. The first layer is a thin metallic layer with the thickness less than its skin depth to make the optical tunneling occur. In this simple structure, the total phase shift at the interface between the first metallic layer and the second dielectric layer is designed to be zero, which results in a destructive interference of backward light to realize no reflected loss. Moreover, in this structure, the slow-light effect appears near the cutoff frequency, which leads to a long absorptive optical distance. From the resonator theory, our structure can also be considered as a resonator and satisfies the critical coupling condition. In this letter, we have fabricated this structure; our experimental results have verified this prediction. Many potential applications can be developed from this phenomenon, such as high-quality laser welding.

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