Absorption Enhancement and Spectrum Selectivity of Refractory Plasmonic Nanostructures

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Abstract **: We demonstrate a broadband spectrum absorber using random structures on refractory plasmonic material (Tungsten) resulting in the absorption efficiency over 90% in the wavelength range from 200 nm to 1100 nm. Numerical simulations for the structure with same parameters agree well with the experimental results. Random nanostructures provide more freedom for enhancing absorption and spectrum selectivity than periodic nanostructures.**

I. Introduction

Enhancing absorption and engineering spectrum properties of materials have evoked great interest of researchers in many fields of thermophotovoltaics and solar thermal applications[1]. Surface plasmonic resonance can produce unique optical characteristics which facilitates a route to achieving appropriate spectrum selectivity and absorption efficiency [2]. Scientific interest is developing toward high temperature for high efficiency thermal to electrical energy conversion[3] such as thermophotovoltaics (TPV)[4]. Applications in the high temperature fields, for example, the maximum energy conversion of solar spectrum needs to limit re-radiation by heating the material above 1200 ℃ for matching narrow bandgap photovoltaic cells[5]. In this paper, we demonstrate a broadband absorption device with random microstructure on refractory material (Tungsten, W) fabricated by femtosecond laser. Experimental results are compared with theoretical analysis using finite difference time domain (FDTD) method.

II. Experimental results

A. Sample Fabrication

Femtosecond (fs) laser was used to induce micro- and nanostructures on the W substrate. The laser has pulse energy of 4.0mJ and temporal duration of 50fs with the wavelength 800 nm. W samples were machined as a cube with side length of 10mm. One of the surfaces of the sample was illuminated by the fs laser to produce micro/nanostructure. The micro morphology of the sample surface was observed by scanning electron microscope (SEM) as shown in Fig.1(a). The surface roughness of the sample was measured by JB-5C roughness tester. The measured root mean square (RMS) value of height with micro/nanostructure is 0.8μm.

B. Sample Optical Characterization

A UNICO UV/VIS/NIR spectrophotometer type UV-2802 was used for measurements absorptions in the UV, visible and near infrared wavelength range. The absorption spectrums of the samples are illustrated in Fig.1(b). It shows that the absorption efficiencies of random microstructure (RMS of 0.8μm) are greater than 90% in the wavelength range from 200 nm to 1100 nm. However, the sample with surface structures RMS of 0.08μm (polished surface) has much lower absorption (less than 70% for $\lambda > 600$ nm).

III. Simulation Analysis

We simulate the optical responses of various random structures and periodic nanostructures using finite difference time domain (FDTD)[6].

A. Random Plasmonic Structures

Fig.2(a) shows the absorption of random structures with different RMS values. The correlation length (Lc) of each structure is set as 0.55μm. We can see that absorption efficiencies are above 85% in the wavelength range of 200 nm to 1500 nm for random structures with RMS of 0.6 to 1.2. However, for longer wavelength range > 1500 nm, the absorption efficiency is strongly dependent upon the value of RMS. Strong resonance peaks can be observed near 2μm for the structure with RMS = 0.8μm, and the resonance peak shifts toward longer wavelength for bigger RMS values. The overall absorption efficiency for wavelength > 2μm is sharply decreased. This property is beneficial for engineering spectrum selectivity in the mid-infrared wavelength range by adjusting the RMS parameter.

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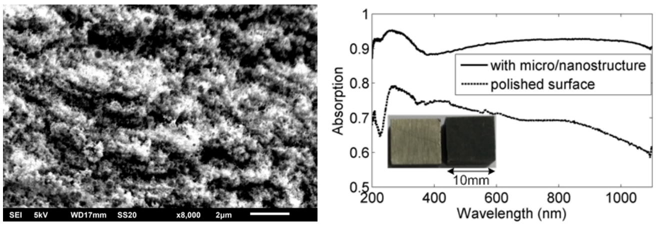

Fig.1. (a) SEM micrograph of the W sample with laser induced random surface structure. (b) Absorption spectrum of laser processed W samples with RMS of 0.8μm and polished surface with RMS of 0.08μm. Inset shows the sample with polished surface (left) and the sample with micro/nanostructure (right).

The absorption of structures of different correlation length is plotted in Fig.2(b). The RMS of all random structures is kept the same as 0.8μm. It can be seen that the absorption efficiency is over 80% in the wavelength range of 200 nm to 1500 nm for different correlation length 0.35 to 0.55. However, the correlation length has much stronger effect on the absorption in the wavelength range from 1.5 to 2.5μm. With correlation length > 0.4, new resonance peaks with strong absorption are excited because the surface features match the resonance wavelength condition. For comparison, the absorption of smooth surface without structures is lower than 50% for the visible and infrared wavelength light (as shown solid line in Fig.2(b)). Therefore, absorption enhancement and spectrum selectivity of refractory materials can be obtained by controlling the RMS and correlation length of the random structures.

B. Periodic Plasmonic Structure

We further simulate the structures with periodic cylinders array based on W substrate. The results show that different parameters, such as height (H), radius (R) and period (P), are important for absorption enhancement. The cylinder height H is fixed 500nm for following simulation. From Fig.3, we can see that, the absorption enhancement can be achieved by adjusting the structure parameters of nanostructure in visible and near infrared wavelength range.

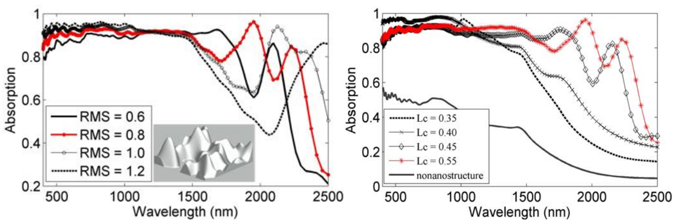

Fig.2. (a) Absorption of random structures with different RMS at correlation length 0.55μm. Inset is the model of random structure. (b) Absorption of random structure with different correlation length at RMS = 0.8μm.

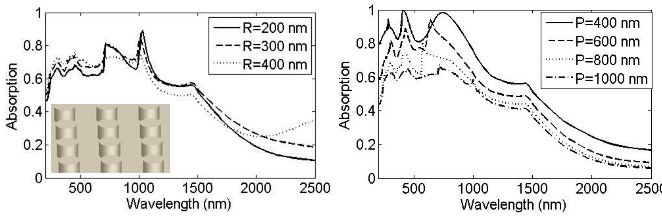

Fig.3. (a) Absorption of the periodic plasmonic structures with different radius setting the period at 1000nm. Inset is the model of period structure. (b) Absorption of the periodic structures with different period at radius = 100nm.

However, the absorption is gradually decreasing toward infrared field beyond the wavelength of 1200nm. It is difficult to excite plasmon resonance modes at different wavelength resulting in broadband absorption enhancement by this kind of periodic structure such as cylinders array. There are no resonant peaks in the mid-infrared for achieving the spectrum selectivity absorption to match narrow bandgap photovoltaic cells, like random structure.

IV. CONCLUSIONS

In conclusion, the random structures on refractory materials can be easily fabricated by fs laser processing which offers flexibility to design and control. Our results indicate that one can design structurally tunable resonant absorbers with enhanced broadband absorption profiles, and particular cut-off wavelength in mid-infrared field. Periodic nanostructures can also be used to enhancing absorption from visible to near infrared field.

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