Brighter Light Sources from Black Metal: Significant Increase in Emission Efficiency of Incandescent Light Sources

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(Received 1 August 2008; published 10 June 2009)

By applying the femtosecond laser blackening technique directly to a tungsten incandescent lamp filament, we dramatically brighten the tungsten lamp and enhance its emission efficiency to approach 100%. A comparison study of emission and absorption for the structured metal surfaces shows that Kirchhoff's law is applicable for the black metal. Furthermore, we demonstrate that we can even obtain partially polarized light as well as control the spectral range of the optimal light emission from the laser-blackened tungsten lamp.

DOI: 10.1103/PhysRevLett.102.234301 PACS numbers: 44.40.+a, 78.68.+m, 81.40.Wx

For over a century, we have known from Kirchhoff's law that the emittance of a surface equals its absorptance in thermal equilibrium [1]. Therefore, the most direct way to enhance the emittance of a thermal light source is to increase the absorptance of its filament surface. Recently, by treating metal surfaces with high-intensity laser pulses, we turned highly reflective metals highly absorptive, creating the so-called "black metals" [2,3]. The essence of blackening metals is to transform a smooth metal surface to a variety of unique surface structures at nano- and micro-length scales that dramatically enhance light coupling into the metals [2,3]. As a significant portion of the surface structures are much smaller than the wavelength of the light, the black metal starts to behave as a metamaterial. It is unclear if Kirchhoff's law that was developed for regular materials can still be applied in the same way here. In this Letter, we show that we indeed dramatically brighten a tungsten incandescent lamp using our blackening technique. The blackening treatment leads to a significant increase of emission efficiency of the tungsten incandescent light bulb to approach 100% efficiency. A comparison study of emission and absorption shows that Kirchhoff's law is still applicable for the black metal. Furthermore, we demonstrate that we can even obtain partially polarized light as well as control the spectral range of the optimal light emission.

In this study, we apply the femtosecond laser structuring technique directly to a tungsten incandescent lamp filament. Following laser treatment, we study light emission of the tungsten lamp and compare its emittance to the absorptance of a tungsten sample prepared under the same experimental conditions. Our experimental setup is shown in Fig. 1(a). Here we use a tungsten ribbon filament incandescent lamp that is typically used for calibrating optical pyrometers [4]. The lamp envelope has a plane window that allows an undistorted laser beam propagating through. The dimension of the lamp ribbon filament is 10×2 mm. To blacken the lamp filament, we use an amplified femtosecond laser system that generates 65-fs pulses at a 1-kHz repetition rate with the central wavelength at 800 nm. The Gaussian laser beam is focused normally onto the filament surface through the plane window. Usually, it takes approximately 20 minutes for the tungsten lamp to reach a stable temperature after being switched on. Therefore, in order to maintain the lamp in equilibrium operation when we measure shot-to-shot emittance change following each shot of structuring, we preheat the lamp to 900 °C and maintain it at this temperature throughout the

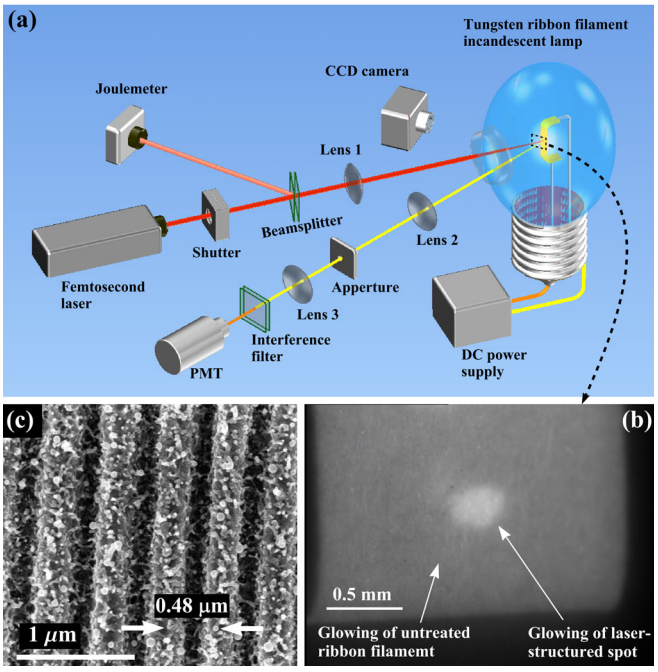

FIG. 1 (color online). (a) Experimental setup for tungsten lamp filament blackening and emittance measurements. (b) CCD image of the glowing tungsten filament with a brighter spot following laser blackening. (c) SEM image of the laser-structured tungsten as for 1(b).

experiment. A CCD camera is used to take optical images of the glowing incandescent filament. For emission measurements, we image the treated filament area onto a photomultiplier tube (PMT) with an optical setup that includes two lenses (Lens 2 and Lens 3), an aperture, and interference filters in front of the PMT, as shown in Fig. 1(a). Lens 2 magnifies the treated filament spot image onto the aperture that selects a treated surface area of about 150 μm in diameter from the central part of the laser-structured spot. The Lens 3 images the aperture onto a sensitive area in the PMT. The PMT is positioned about 8° off the filament surface normal. In this Letter, we refer to laser fluence as a single-pulse fluence defined as $F = E/S$, where E is the single-pulse energy incident on the filament and S is the beam area on the filament. The single-pulse energy E is monitored by splitting a certain amount of the incident light to a joulemeter.

Following femtosecond laser blackening, we see a dramatic increase of brightness on the blackened area on the tungsten filament. This can easily be seen with even the naked eye under dim operation of the lamp. Figure 1(b) is a CCD image of the glowing tungsten filament with a spot treated by 400 laser pulses at the fluence of $F = 0.17$ J/cm^2. This image clearly shows that the treated area is much brighter than the surrounding untreated area. Note, to avoid noticeable contamination to the bulb envelope from the ablated filament material, we only use moderate fluence and number of applied pulses to partially blacken the filament surface. To characterize the emittance enhancement quantitatively, we measure the PMT signal readouts from both laser treated and untreated areas, labeled as U_{TR} and U_{UN}, respectively. We define an emittance enhancement coefficient due to surface blackening as $U_{\mathrm{TR}}/U_{\mathrm{UN}}$. The value of $U_{\mathrm{TR}}/U_{\mathrm{UN}}$ is measured at different fluence as a function of the number of applied laser pulses. The emittance enhancement coefficients are determined at three different wavelengths of 400, 630, and 800 nm by inserting narrow bandpass interference filters centered at these wavelengths. Furthermore, we also measure the integrated light emission in the entire visible spectral region of 400–700 nm. Figure 2(a) shows the dependence of the emittance enhancement coefficient on the number of pulses at $F = 0.17$ J/cm^2. As can be seen from the figure, emittance of the tungsten filament is enhanced at all the studied wavelengths following the blackening of the filament surface at this moderate fluence level.

As discussed in the introduction, Kirchhoff's law was originally developed based on the study of regular materials. Since the black metal can behave partially as a metamaterial, it will be fundamentally interesting to compare emittance and absorptance of the black metal in our case and see if Kirchhoff's law is still applicable here. To do so, we study laser-induced absorptance change of a tungsten sample with the same initial surface smoothness as the lamp filament. Using a calorimetric technique discussed in our previous work [2], we directly measure absorptance

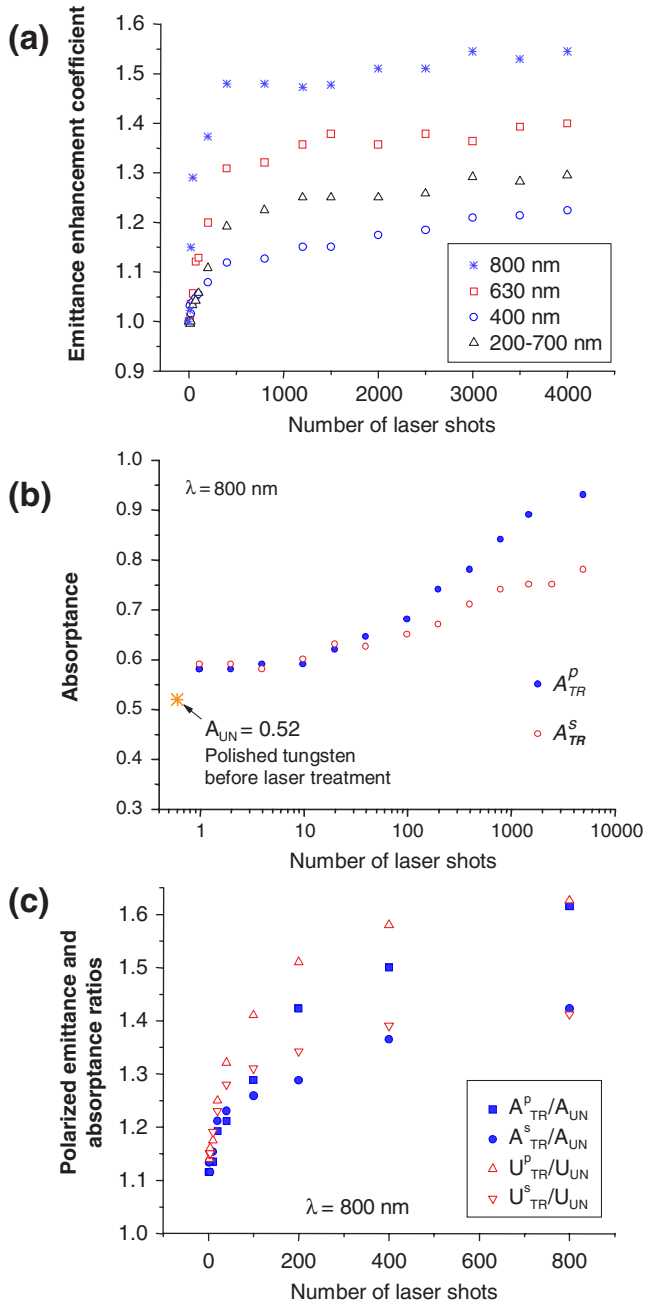

FIG. 2 (color online). Absorptance and emittance measurements of tungsten treated at the laser fluence of 0.17 J/cm^2. (a) Emittance enhancement coefficient as a function of the number of applied laser shots for wavelengths of 800, 400, 630 nm and for the whole visible spectrum of 400–700 nm. (b) Absorptance as a function of the number of applied laser pulses at 800 nm. (c) Emittance and absorptance enhancement coefficients at p and s polarizations as a function of the number of applied laser pulses at 800 nm.

of both the treated and untreated areas of the tungsten sample at our laser wavelength of 800 nm. Briefly, absorptance is measured in the following method. After the sample is blackened, the laser fluence is reduced to a level

much below the damage threshold. The treated spot is then irradiated again using a train of the low-fluence laser pulses. The absorbed energy from this low-fluence pulse train, E_A, is determined calorimetrically [2]. To measure the incident energy E_I, a small fraction of the incident pulse train energy is split off by a beam splitter and measured with a joulemeter. Having measured E_I and E_A, the absorptance of the treated spot can be found as $A = E_A/E_I$. In our experiment, surface structures are produced using p-polarized light, while the absorptance is measured with both p- and s-polarized light. Figure 2(b) shows the enhancement in absorptance for the tungsten surface following femtosecond laser blackening. Absorptance of the unstructured tungsten surface, A_{UN}, is measured to be about 0.52, and this value agrees well with the table value of 0.45–0.6 for normally incident light at 800 nm [5]. Following laser blackening at the fluence of 0.17 J/cm^2, the figure shows that the absorptance is significantly enhanced for both p- and s-polarization probes, with absorption increasing to over 90% for the p-polarization probe. Similar to the emittance enhancement coefficient defined above, we also define an absorptance enhancement coefficient as $A_{\mathrm{TR}}/A_{\mathrm{UN}}$, where A_{TR} and A_{UN} are the absorptance of the treated and untreated areas, respectively. The absorptance enhancement coefficient, $A_{\mathrm{TR}}/A_{\mathrm{UN}}$, is plotted in Fig. 2(c) for both p and s polarizations at 800 nm. To directly compare the absorptance enhancement at the two polarizations, we also measure the tungsten lamp emittance for both p and s polarizations by placing a polarizer in front of the PMT, and the emittance enhancement ratio, $U_{\mathrm{TR}}/U_{\mathrm{UN}}$, at 800 nm is also plotted in Fig. 2(c). We can see that the emittance and absorptance show a similar amount of enhancement, demonstrating that Kirchhoff's law is general and applicable for the black metal. We notice a somewhat faster increase in the emittance ratio than the absorptance ratio, and this is due to what we pointed out earlier that we blacken the filament in the emittance experiment when the lamp is preheated to 900 °C, while the absorptance experiment is performed at room temperature. Since we enhance the absorption of tungsten to nearly 100%, light emission from the tungsten lamp can be enhanced to its highest possible emission efficiency as well.

One interesting aspect of light emission from the laser-treated tungsten filament is that the enhanced light emission is wavelength dependent. We notice that the light enhancement is most pronounced at 800 nm, less significant at 630 nm, and least at 400 nm. To determine what causes the enhanced emittance and absorptance as well as their polarization effects, we perform a detailed scanning electron microscope (SEM) study of surface structures produced under various experimental conditions. As an example, Fig. 1(c) shows a SEM image of a laser-treated spot under the same condition used for both the emittance and absorptance measurements above. We can see that the treated surface is nearly entirely covered by laser-induced periodic surface structures (LIPSSs) superimposed with fused nanostructures, and this surface pattern is also the structure that causes the enhanced glowing spot in Fig. 1(b). LIPSS formation on solids has been observed in the past mainly using relatively long laser pulses [6–9]. Recently, LIPSS generation using femtosecond lasers has been demonstrated on semiconductors [10,11], dielectrics [11,12], and metals [2,13,14]. Most interestingly, in contrast to smooth gratings produced by longer laser pulses, we found, for the first time, a unique type of LIPSSs covered with nanostructures, the so-called nanostructure-covered LIPSSs (NC-LIPSSs) [13], as seen here on tungsten. The nanostructures on metals can couple free-space waves to surface plasmons [15] and inversely, they can couple thermally excited surface plasmons to free-space thermal radiation. The nanostructures of NC-LIPSSs produced on the tungsten filament contribute to the observed enhanced thermal emission.

Since it is difficult to characterize the wavelength effect of emission by measuring the signal from an isolated blackened spot on the tungsten lamp, we perform a more general study on spectral absorptance. For this purpose, we blacken a tungsten surface with femtosecond pulses over a large circular area of 24 mm in diameter by scanning the sample. We again use the same fluence of 0.17 J/cm^2 as in the above emission and absorption experiments, where NC-LIPSSs are the dominating structures. After the laser treatment, the total reflectance of the sample is measured over the wavelength range of 250–2500 nm using a Perkin-Elmer spectrometer (Lambda 900) with an integrating sphere, and the result is shown in Fig. 3. For comparison, Fig. 3 also shows the wavelength dependent reflectance of a mechanically polished sample without laser treatment. We can see that the reflectance of the untreated tungsten surface is about 0.52 (absorptance = 0.48) at 800 nm, and this value agrees with our absorptance measurement with the calorimeter technique, as shown in Fig. 2(b). Figure 3

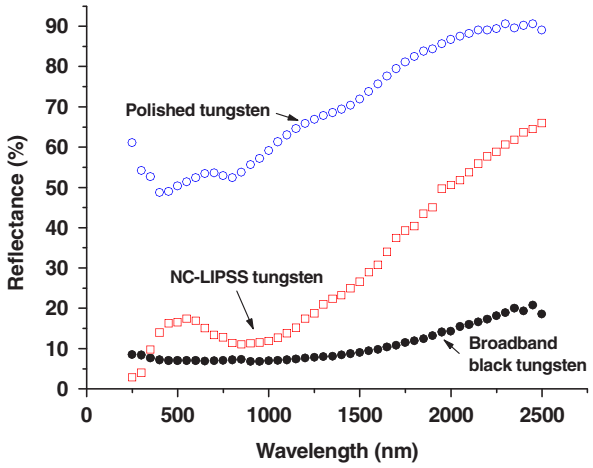

FIG. 3 (color online). Spectral reflectance measurements of untreated tungsten, tungsten covered with NC-LIPSSs, and the black tungsten.

shows that reflectance following 800-nm light treatment decreases over the entire wavelength range measured, but most noticeably in the wavelength range of 500–1300 nm. This indicates that following 800-nm light treatment, absorptance (1 − reflectance) and hence emission of tungsten will increase most noticeably over the 500–1300 nm wavelength range.

Another interesting feature from the laser-treated tungsten lamp is that light emission is polarization dependent. From Fig. 2(c), we can see that the enhancement in emittance and absorption is higher for *p* polarization than for *s* polarization. We believe that NC-LIPSSs also play the dominant role in the polarization effect. NC-LIPSSs can effectively support surface plasmons, and hence contribute to the enhancement in light absorption and emission. In case of absorption, this polarization effect is caused by the fact that the most efficient coupling of free-space light to surface plasmons occurs when the polarization of the incident light is parallel to the grating vector. For the inverse process (emission), thermally excited surface plasmons with electric field components parallel to the NC-LIPSS grating vector will couple into free-space thermal radiation most efficiently, causing a polarization effect in emitted light.

To explore if we can produce an ideal light emitter with a flat wavelength response curve, we also produce a nearly totally black tungsten sample. The spectral dependence of the total reflectance of this black tungsten is shown in Fig. 3. We can see that the black tungsten has a nearly uniform low reflectance over the entire wavelength range measured (250–2500 nm). Note, the black metals discussed in this Letter are produced by fs laser irradiation only. Other work has showed the blackening of silicon using corrosive gases along with a laser to produce chemically etched microstructures [16]. The black metals produced with our technique have different surface structures and are free from chemical contaminations, which is important for incandescent light filaments. Also, to perform the spectral dependence measurements, a relatively large blackened area needs to be processed and we can only optimize the experimental condition for maximum blackness by visual examination. We believe that the remaining few percent of reflectance can be suppressed with further optimizing the processing conditions. SEM studies of the black tungsten show that the blackened surface contains a combination of nano- and microstructures. The uniform increase of absorptance of the black tungsten promises to produce extremely efficient ultrabroadband light sources with flat spectral response.

In summary, by applying the femtosecond laser blackening technique directly to a tungsten incandescent lamp filament, we dramatically brighten the tungsten lamp and enhance its emission efficiency to approach 100%. A comparison study of emission and absorption for the structured metal surface shows that Kirchhoff's law is applicable for the black metal. Furthermore, we demonstrate that we can even obtain partially polarized light as well as control the spectral range of the optimal light emission from the laser-blackened tungsten lamp. Our study shows that metal blackening is a unique way of producing a brighter, more efficient, and spectrally controllable source of thermal radiation.

We would like to acknowledge the support of spectral measurements from K. Marshal and J. Shojaie. This work was supported by the US Air Force Office of Scientific Research.

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