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Thermal Emitter Design based on Gap and Spacer Plasmon Mode Coupling

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Abstract: We propose tungsten based thermal emitters. With a simple three-layer metal-dielectric-metal design we obtain over 0.9 emittance between 0.5 and 2.2 μm, which is achieved by strong coupling between gap and spacer plasmon resonances.

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1. Introduction

Thermal emitters, which are devices to convert heat into radiation, are essential in many applications, including thermal imaging, sensing, and energy conversion in thermophotovoltaic (TPV) systems. The design of thermal emitters is actively pursued in order to offer more flexible control over the directional and spectral properties of thermal radiation, and to fit the needs of those applications.

In particular, the thermal emitter is a key component on a TPV system, which converts heat into electric energy viaa photovoltaic cell [1]. If a TPV emitter is an ideal blackbody emitter, significant amount of emission power is wasted, since photons with energy below the bandgap of the PV cell (E_g, with corresponding wavelength $\lambda_g = hc/E_g$, where h is Planck's constant, c is the speed of light.) cannot generate electron-hole pairs. Therefore, to maximize the TPV efficiency, the emitter has to emit photons with energy higher than E_g as much as possible, and emit photons with energy lower than E_g as little as possible. Alternatively speaking, it is desirable to have a selective emitter with high emittance at wavelengths shorter than λ_g, and low emittance at wavelengths longer than λ_g. Other than the spectral selectivity, the emitter needs to operate at high temperature. Therefore refractory metals such as tungsten are often selected as emitter materials. Various methods have been proposed to control the spectral selectivity of emitters, such as microcavities, photonic crystals, and gratings [2–5].

In this paper, we investigate tungsten based thermal emitter designs with nanostructures to achieve high emittance over a wide range of wavelengths shorter than λ_g. First a design with pure tungsten with tapered gratings, with groove width at the bottom equals to the periodicity of the grating, is proposed, with the capability of exciting multiple gap plasmon modes. Then we show that by inserting a thin dielectric spacer, additional resonances are excited within the spacer, and coupled to existing gap resonances. The strong coupling between gap and spacer modes leads to expanded bandwidth of high emittance, which differentiates our design from existing proposals.

2. Emitter Designs

Tungsten is a refractory metal widely used in many applications including TPV emitters. Various nanophotonic designs based on tungsten have also been proposed toward selective emission with high emittance in the visible and infrared regime. In particular, grating structures in 1D and 2D have been previously investigated, where significantly enhanced emission compared with flat tungsten surface is realized owing to several physical mechanisms, including cavity resonances, propagating surface plasmon polaritons, and localized surface plasmon resonances (LSPRs). LSPRs can be excited at both vertical and horizontal metal-dielectric boundaries, and the resonant frequencies can be tuned via geometrical design [5,6]. Moreover, the nanostructures to support LSPRs can be made to be subwavelength, therefore more resonances can be excited within the same area, creating stronger absorption effect. Previously, it was shown that rectangular deep gratings support LSPR modes, and the resonant frequencies can be tuned by filling ratio of the grating. Hybrid gratings with two stacked layers of the same periodicity but different filling ratio has also been proposed for enhanced emission over a broader bandwidth [4].

In this paper, we proposed two emitter designs based on tungsten. As shown in Fig. 1, design A has trapezoid shaped grating structures, where the tungsten grooves touch each other at the bottom and are linearly taper down to the top. The geometrical parameters are also shown in the figure. Design B has the same grating layer as design A, but has an

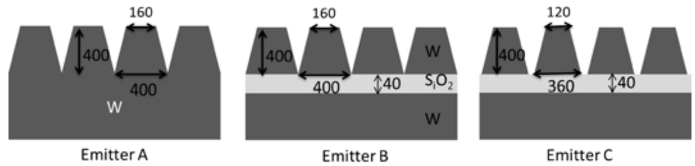

Fig. 1. Cross section of proposed emitters and corresponding dimensions (given in *nm*). Periodicity of the top layer is 400 *nm* for all cases.

additional thin layer of SiO2 between the grating layer and the substrate. As reference, design C is similar to design B, but with narrower tungsten grooves on the top layer, such that there is a gap between neighboring grooves.

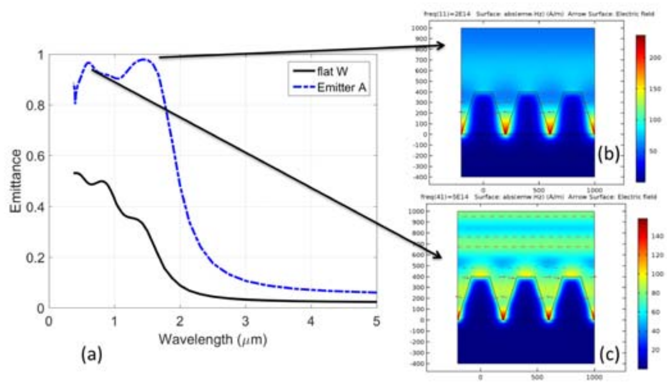

Fig. 2. (a) Emittance spectrum of emitter A (and flat W surface as reference), and the field distribution at wavelength (b) 1.5 μm, and (c) 0.6 μm.

Similar to rectangular shaped grooves, multiple LSPR modes are also supported in the gaps between neighboring grooves in the tapered design A, thus high emittance is obtained at the resonances, as shown in Fig. 2(a). On the other hand, these modes are less well defined due to the gradually varying width of the gap, therefore the emittance drop between resonances is not significant. As a result, over 0.9 emittance is obtained between 0.5 and 1.7 μm. The emittance spectrum of flat tungsten is also plotted for reference. The corresponding field distributions at the two emittance peaks at 1.5 μm and 0.6 μm are plotted in Fig. 2(b) and (c), showing strong localization of field due to the excitation of LSPR modes.

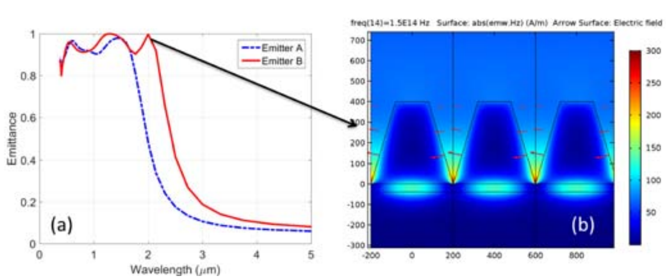

Fig. 3. (a) Comparison of emittance of emitter A and B, and (b) field distribution of emitter B at wavelength 2 μm.

It has been shown before that a three-layer structure, with a metallic top grating layer and a metallic substrate, sandwiched with a dielectric layer in between, can support LSPR modes too [5]. With design B, we show that both LSPR modes in the top layer gap and the middle layer spacer can be excited. Light is coupled to the LSPR in the spacer through the mode in the gap. The extra resonant peak due to the LSPR in the spacer extends the bandwidth of high emittance. As shown in Fig. 3(a), the lower bound of high emittance over 0.9 is extend to 2.2 μm, which matches well to the bandgap of commonly used TPV cell of InGaSb. In Fig. 3(b), the strong field localization at 2.0 μm around both gap and spacer indicates the aforementioned mode coupling between gap and spacer modes.

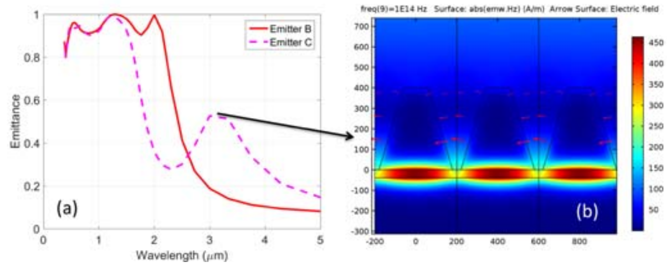

Fig. 4. (a) Comparison of emittance of emitter B and C, and (b) field distribution of emitter C at wavelength 3 μm.

On the contrary, when there is a gap between neighboring grooves of the top grating layer, which is commonly used in previous studies [5], the resonant peak of the emittance spectrum is shifted to much longer wavelength, which is undesirable for TPV emitter. As shown in Fig. 4(a), the resonant peak shifts from 2.0 μm to 3.0μm in design C. The field distribution at that peak shown in Fig. 4(b) indicates strong localization in the spacer region only. Therefore the mode coupling between gap and spacer modes is only significant in the case of design B.

All simulations shown in the paper are done in COMSOL multiphysics, and the permittivity of tungsten is described by a Drude-Lorentz model fitted with experimental data [7]. At each wavelength, the emittance is obtained from the absorptance $\alpha = 1 - r - t$, where r is the reflectance, and t is the transmittance. The normal incident wave is TM-polarized with magnetic field perpendicular to the plane of the structures.

3. Conclusions

In conclusion, we proposed thermal emitter designs based on tapered tungsten gratings with bottom width equal to the periodicity, and a dielectric spacing layer. We achieved higher than 0.9 emittance over a wide spectrum between 0.5 to 2.2 μm, suitable for TPV applications. By investigating the emittance peaks and corresponding field distributions, we show that the improved performance is due to the strong coupling between gap and spacer plasmon resonances, which is a distinct feature compared with previous designs.

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