Highly efficient light emission at $\lambda = 1.5 \, \mu m$ by a three-dimensional tungsten photonic crystal

S. Y. Lin, J. G. Fleming, and I. El-Kady

Sandia National Laboratories, MS 0603, P.O. Box 5800, Albuquerque, New Mexico 87185

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For what is believed to be the first time, a three-dimensional tungsten photonic crystal is demonstrated to emit light effectively at wavelength $\lambda = 1.5 \, \mu m$. At a bias of $V = 7 \, V$, the thermal emission exhibits a full width at half-maximum of $\Delta \lambda = 0.85 \, \mu m$. Within this narrow band, the emitted optical power is 4.5 W and the electrical-to-optical conversion efficiency is $\sim 22\%$ per emitting surface. This unique emission is made possible by a large, absolute bandgap in the infrared $\lambda$ and flat photonic dispersion near the band edges and in a narrow absorption band. © 2003 Optical Society of America

Light emitters operating in the near-infrared wavelength regime ($\lambda = 1–2 \, \mu m$) are almost universally based on semiconductor materials. To vary the emission wavelength, researchers often apply the principle of electronic bandgap engineering to obtain the appropriate electronic bandgap energy. A thermal radiator can also emit light in the near infrared, if it is heated to a temperature of $T \sim 1500 \, K$. Nonetheless, this radiation process is not efficient at producing narrowband emission. For example, a blackbody thermal radiation spectrum at $T = 1500 \, K$ has a full width at half-maximum (FWHM) of $\Delta \lambda = 2.3 \, \mu m$, and $\sim 75\%$ of its total emission power is distributed in the mid infrared ($\lambda > 2 \, \mu m$). However, it has been suggested that the principle of photonic bandgap engineering can be applied to modify the thermal radiation pattern. In particular, a complete photonic bandgap is effective in trapping light in the infrared and thus reduces radiation loss in this regime. Second, nearly flat-band photonic dispersion ($\omega$ versus $k$, where $\omega / k \sim 0$) has been proposed to facilitate light emission at a narrow band. Flat photonic dispersion can be found at the photonic band edges and at a narrow allowed band. If both effects are successfully implemented, a thermal emitter with a narrow band and high efficiency can be realized.

In this Letter a tungsten three-dimensional (3D) photonic crystal is demonstrated to emit light effectively at wavelength $\lambda = 1.5 \, \mu m$. At a bias of $V = 7 \, V$, the emission exhibits a FWHM of $\Delta \lambda = 0.85 \, \mu m$. Within this narrow band, the emitted power is 4.5 W and the electric-to-optical conversion efficiency is $\sim 22\%$ per emitting surface. The high efficiency and high power emission at $\lambda = 1.5 \, \mu m$ are attributed to two unique photonic bandgap effects. The large, absolute photonic bandgap is effective in suppressing mid-infrared emission ($\lambda > 2 \, \mu m$), and, at the same time, the emission is enhanced in a narrow band because of enhanced density of photon states, $D(\omega)$.

The 3D tungsten photonic crystal is fabricated by use of a modified silicon process. In the first step, a layer of silicon dioxide is deposited, patterned, and etched to create a mold. The mold is then filled with a 500-nm-thick chemical-vapor-deposited tungsten film. The structure is then planarized by use of a chemical–mechanical polishing process. At the end of the process, the silicon dioxide is released from the substrate and the sample is a freely standing thin film. In Fig. 1, a scanning electron micrograph image of the fabricated sample is shown. The one-dimensional rods represent the shortest (110) chain of atoms in a diamond lattice. The stacking sequence is such that every four layers constitute a unit cell.

The experimental reflection, transmission, and emission spectra of the 3D photonic crystal are taken with a standard Fourier-transform infrared spectrometer at $\lambda = 0.8–15 \, \mu m$. For the emission measurement, the sample is mounted so that it is thermally and electrically isolated from its surroundings. Thermal heating of the air and convection are minimized by placing the sample in a vacuum chamber pumped to $\sim 10^{-5} \, Torr$. For power density measurements, a commercially available Gentec powermeter, calibrated to within $5\%$, is used.

In Fig. 2, the reflection (black curve) and transmission (blue curve) spectra of an eight-layer 3D photonic-crystal sample are shown. The high reflectance for $\lambda > 3 \, \mu m$ indicates the existence of a large photonic bandgap. Such a 3D metallic bandgap is a complete bandgap and is effective ($\sim 30 \, dB/unit cell$) in blocking light fully in all directions and for both polarizations. The reflectance shows a dip at $\lambda \sim 2.5 \, \mu m$.
correspondingly, the transmittance is low in the bandgap and exhibits a small peak at $\lambda \sim 2.5$ $\mu$m and a sharp peak of $\sim 10\%$ at $\lambda \sim 1.75$ $\mu$m. The sharp transmission band is indicative of flat photonic dispersion (i.e., $\omega$ versus $k$) associated with a narrow allowed band. In the following, the experimental data are compared with results of a modified transfer-matrix calculation. This new calculation method can handle the complex dielectric constant of tungsten material in our 3D photonic crystal.

In Fig. 3, computed results of the reflection (black curve), transmission (blue curve) and absorption (red curve) spectra for the same sample are shown. The computed reflection and transmission spectra agree well with the measured ones. In particular, the reflectance is high for $\lambda > 3$ $\mu$m (first photonic bandgap) and shows a slight dip at $\lambda \sim 2.5$ $\mu$m, a peak at $\lambda \sim 2.2$ $\mu$m (second photonic bandgap), and finally a sharp drop at $\lambda \sim 2$ $\mu$m. The first and second band edges are closely spaced, leading to a reflectance dip, a transmission peak, and finely resolved doublet absorption peaks, all at $\lambda \sim 2.5$ $\mu$m. The strong absorptance of $\sim 40\%$ is due to an enhanced photon density of states, $D(\omega)$, at the band edges. Additionally, there exists a narrow transmission peak at $\lambda \sim 1.7$ $\mu$m and a corresponding absorption band at $\lambda_2 \sim 1.5$–1.9 $\mu$m (indicated by red arrows). The high absorptance of $\sim 80\%$ at $\lambda \sim 1.5$–1.9 $\mu$m is due to both high $D(\omega)$ and high tungsten material absorption at these wavelengths.

To achieve emission, we biased the photonic-crystal sample by applying a voltage across the sample and heating it through joule heating. The emission intensity is uniform across the entire sample, as shown in the inset of Fig. 4(b). The photograph shows a slight visible emission at the tail of the emission peak. In Figs. 4(a) and 4(b), emission spectra taken at low and intermediate bias, respectively, are shown. At $V = 0.25$ $V$, the emission spectrum consists of broad emission near $\lambda \sim 3$–6 $\mu$m and a peak at $\lambda_1 \sim 2.5$ $\mu$m. As $V$ is increased to 0.5 and then to 0.75 $V$, an additional emission peak appears at $\lambda_2 \sim 1.9$ $\mu$m. The broad emission is attributed to thermal emission from the surface layer of the sample, which experiences little photonic bandgap effect. The two sharp peaks correspond well to the absorption peaks predicted in Fig. 3. As $D(\omega)$ affects both the emission and the absorption rate, the close agreement of emission and absorption peaks is expected.

The intensity evolution of both peaks is worth noting. At $V = 0.25$ and $V = 0.5$ $V$, the $\lambda_2$ emission is weaker than the $\lambda_1$ emission. The respective intensities of the emissions become nearly equal at $V = 0.75$ $V$, and eventually $\lambda_2$ emission dominates the spectrum at $V = 1$–3 $V$. In short, as $V$ is increased, or equivalently as the input electric power is raised, the $\lambda_2$ peak increases at a faster rate than the $\lambda_1$ peak. A similar finding was also observed previously but at a longer wavelength of $\lambda \sim 4$ $\mu$m. It is noted that, while the $\lambda_1$ peak remains at the same
wavelength as V is increased, the $\lambda_2$ peak is shifted slightly to a lower wavelength at $\lambda_2 \sim 1.9-1.75 \ \mu m$. This wavelength shifting is further examined below at higher biases.

In Fig. 5, the emission spectra taken at even higher biases of V = 5, 6.7 V are shown. The $\lambda_1$ peak becomes an indiscernible weak shoulder. Meanwhile, the $\lambda_2$ peak continues to shift from $\lambda_2 \sim 1.7 \ \mu m$ at $V = 5 \ \text{V}$ to $\lambda_2 \sim 1.5 \ \mu m$ at $V = 7 \ \text{V}$. The wavelength shifting from $\lambda_2 \sim 1.9 \ \mu m$ to $\sim 1.5 \ \mu m$ corresponds to scanning of the absorption band (indicated in Fig. 3 by the red arrows) as V is increased. At $V = 7 \ \text{V}$, the emission has a FWHM of $\Delta \lambda_1 \sim 0.85 \ \mu m$ and an emission power of 4.5 W within the narrow band.

The operating principle of this class of tungsten photonic-crystal light emitter is different from that of the conventional LED. A LED is based on semiconductor technology and relies on radiative recombination of electrons and holes to achieve light emission. Quite differently, a tungsten photonic-crystal emitter is based on metals. It achieves narrowband light emission through spectral modification of thermal radiation. The challenge for realizing such a photonic-crystal emitter is in nanofabrication. To achieve visible light emission, our metallic structure needs a minimum feature size of $\sim 100 \ \text{nm}$. However, one of the great advantages of this photonic-crystal approach is its ease of wavelength scalability. For the same tungsten material, we can vary the emission wavelength from $\sim 5 \ \mu m$ to 500 nm by simply scaling the minimum feature size from $\sim 1 \ \mu m$ down to 100 nm.

In summary, a tungsten 3D photonic crystal has been successfully demonstrated to emit light preferentially at wavelength $\lambda = 1.5 \ \mu m$. The tungsten photonic-crystal light emitter exhibits high efficiency of $\sim 22\%$ per surface and high output power of 4.5 W. This demonstration of high efficiency and high power is made possible by the presence of an absolute bandgap in the infrared and enhanced density of photon states near the band edges and in a narrow absorption band.

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