2014年9月22日 Nature Materials, News and Views

THERMAL EMISSION

Ultrafast dynamic control

Control of thermal emission with microsecond switching times has been achieved by using sub-band transitions in composite quantum-well and photonic-crystal structures.

Ognjen Ilic and Marin Soljačić

The most familiar example of a thermal emitter is the Sun. Because of the thermal motion of charged particles, its 5,800-K hot surface most strongly emits radiation in the green (at a wavelength around 500 nm). More generally, the relationship between temperature of a black body and wavelength of emission is captured by Wien's displacement law: the peak wavelength of emitted light is inversely proportional to a black body's absolute temperature. Hence, peaks of emission of hotter stars are shifted towards the blue, and those of colder stars towards the red. Thermal emission can also be controlled in the absence of a temperature change by incorporating periodic features with length scales comparable to the wavelength of thermally emitted light[1–3]. Writing in *Nature Materials*, Susumu Noda and colleagues have now pushed this concept a step further. They developed a composite structure that combines photonic crystals and quantum wells, allowing for dynamic control of thermal emission at speeds that are more than four orders of magnitude faster than conventional means of temperature modulation[4].

Photonic crystals exhibit a photonic bandgap that prevents light of certain frequencies from propagating through the crystal. Also, because of the unique way crystal periodicity affects the flow of light, photonic crystals can alter emission in drastic ways[5]. For example, the introduction of a patterned array of holes can enhance significantly the emission of a block of metal[3] (Fig. 1a). The properties of the periodic structure, such as the shape and size of the individual periodic elements, and the lattice type and constant, directly determine the position and the size of the photonic bandgap as well as the location of the photonic crystal resonances. These resonances, in turn, influence optical properties of the structure, such as reflectance, transmittance and emittance. Once the desired pattern is implemented, however, this approach doesn't allow for dynamic control of the resulting emission spectrum. Noda and co-authors have solved this issue by adding a multiple quantum well structure to an otherwise typical photonic crystal lattice. The composite structure is formed of thin gallium arsenide layers sandwiched between a wider-bandgap material, aluminum gallium arsenide, that confines the electrons to move in essentially two dimensions. Such confinement results in the formation of discrete energy sub-bands[6], and it is the transition between these sub-bands that the authors exploit to modify thermal absorption. At the same time, a triangular lattice of air holes is introduced into the quantum-well layer, turning the structure into a photonic crystal (Fig. 1b). By carefully tuning the parameters of the quantum-well structure — such as its width, depth and number of layers — the authors match the absorption associated with a sub-band transition to one of the emission peaks of the photonic crystal. These emission peaks are manifestations of photonic crystal resonances, which have the benefit to both sharpen and enhance the spectral features of absorption.

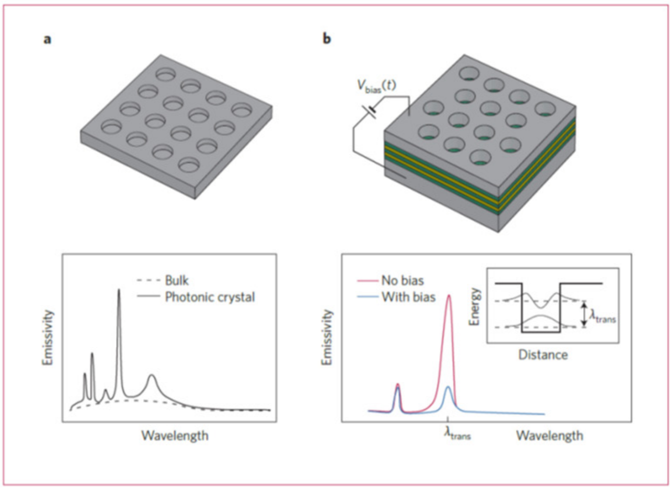

Figure 1 | Structures for the control of thermal emission and emissivity spectra. **a**, The emission (solid line, bottom) from a metallic photonic crystal (top) has strong spectral selectivity relative to the emission of a bulk metal (dashed line, bottom). The shape of the periodic structure determines the positions of the emission peaks, and emission can be controlled by modulating the temperature $T(t)$ of the entire device over time t. **b**, The composite structure of Noda and colleagues, which incorporates a multiple-quantum-well structure (green and yellow layers, top), allows for dynamic control of emission (bottom) by means of electrical tuning (through a time-dependent voltage bias, $V_{bias}(t)$). The wavelength λ_{trans} of the inter-sub-band transition of the multiple-quantum-well structure (inset) is matched to one of the resonances of the photonic crystal, thereby enhancing the emission of light at that wavelength.

Traditional means of varying thermal emission of radiation by temperature modulation are limited to approximately hundred cycles per second, and are only possible in objects with a small thermal mass[7]. Noda and co-authors' design dramatically outperforms, both in speed and magnitude, any previous methods of controlling thermal emission. The authors achieved such fast variation in emission by directly controlling the absorption rate of the quantum wells through electrical modulation with an external bias voltage. They report modulation rates that are as high as several hundred kHz, and argue that further optimization of the structure could increase this value to more than 10 MHz. Moreover, the magnitude of the variation of the emittance is $\Delta\varepsilon = 0.5$ (a perfect reflector has emittance of 1 whereas that of a perfect absorber is 0), an order of magnitude larger than that of previously reported methods[8]. The result is of fundamental interest, as it allows basic quantities in thermal physics, such as the amount of emitted heat by a body at a given temperature, to be dynamically controlled without changing the temperature of the emitting body itself. Furthermore, this can be achieved at rates that are much faster than the time required to achieve thermal equilibrium, opening avenues for the study of non-equilibrium heat processes, in particular for applications in spectroscopy as well as chemical and biological sensing.

Still, the wavelength tunability that Noda and colleagues' structures allow is constrained by the fact that sub-band transitions are generally restricted to infrared wavelengths and to transverse magnetic polarization of light, and by the structures' limited potential for operation at high temperatures. Furthermore, the wavelength selectivity in these structures is still static: both the photonic crystal and the quantum-well layers are specifically — and irreversibly — designed to switch thermal emission at a specific wavelength. Although photonic crystals can be designed with almost arbitrary resonances, dynamic control of the wavelength of these resonances remains a challenge. Nevertheless, the work of Noda and co-workers is a marked progress towards a more complete control of thermal emission. ❐

Ognjen Ilic and Marin Soljačić are at the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
e-mail: ilico@mit.edu; soljacic@mit.edu

References

1. Arpin, K. A. *et al. Nature Commun.* **4,** 2630 (2013).
2. Fan, S., Raman, A. & Yu, Z. *Proc. Natl Acad. Sci. USA* **107,** 17491–17496 (2010).
3. Chan, D. L. C., Soljačić, M. & Joannopoulos, J. D. *Opt. Express* **14,** 8785–8796 (2006).
4. Inoue, T., De Zoysa, M., Asano, T. & Noda, S. *Nature Mater.* **13,** 928–931 (2014).
5. Joannopoulos, J. D., Meade, R. D. & Winn. J. N. *Photonic Crystals: Molding the Flow of Light* (Princeton Univ. Press, 1995).
6. West, L. C. & Eglash, S. J. *Appl. Phys. Lett.* **46,** 1156–1158 (1985).
7. Hildenbrand, J. *et al. IEEE Sensors J.* **10,** 353–362 (2010).
8. Vassant, S. *et al. Appl. Phys. Lett.* **102,** 081125 (2013).