whether the fluorescence is enhanced or suppressed[11]. All fluorophores have a quantum efficiency that describes the ratio of spontaneous emission (a radiative loss process) to all loss processes — including non-radiative ones — through which an excited fluorophore loses energy. Close proximity to a metal can significantly affect the quantum efficiency, for example by modifying radiative and non-radiative loss processes[12]. Depending on the geometry of the metal and the distance of the fluorophore from the boundary, the local electric field may be enhanced, for example in a bowtie resonator, leading to more energy absorption by the fluorophore and perhaps more spontaneous emission. The interaction between excitation light, fluorophore and metal can be described classically, unless the fluorophore is very close to an isolated metal subnanoscale particle. The dipole moment of the fluorophore couples to the metal to produce spatial oscillations of electron density, which may be either radiating surface plasmon polaritons (SPPs) or localized plasmons, depending on the geometry. All of these local excitations are subject to damping. SPPs cannot be excited directly on a flat metal surface in air because it is not possible to match the momentum of the incoming photons in the plane to the larger momentum of SPPs. If the metal surface is not flat but is structured on the nanoscale (as with a metal nanoparticle or bowtie antenna), the excitation light can excite SPPs or localized plasmons directly, through the spatial frequencies provided by the particular profile of the surface. These plasmons can produce a significant enhancement to the local electric field and increase the excitation of the fluorophore. If the enhanced excitation is greater than any increased non-radiative damping (caused by close proximity to the metal), then an increase in fluorescence will be observed. A fluorophore close to a smooth metal surface is generally quenched because energy couples to plasmons that cannot re-radiate, and Ohmic losses — electrons dissipating energy from the electromagnetic oscillations by heating the metal — increase the non-radiative loss rate. If the fluorophore is more than approximately one wavelength away from the surface, there is negligible quenching of its fluorescence.

Kinkhabwala *et al.* have demonstrated significantly enhanced emission from fluorescent molecules by placing them in the gap of a bowtie nano-antenna. By using dye molecules with low intrinsic quantum efficiency, they were able to show a fluorescence enhancement much larger than that possible if a dye with high quantum efficiency was used. The bowtie enhances emission in more than one way. First, the excitation light produces a strong field enhancement in the bowtie gap. Second, the bowtie functions as an optical antenna to enhance radiative emission from the fluorophore. This process is strongly mediated by plasmons, which enhance emission from the bowtie.

The ability to fabricate a large number of bowties on a single substrate allows many individual molecules to be observed. In this study, fluorophores were randomly distributed on the surface and some, at least, were optimally placed within the bowtie gaps. In the future, controlled placement of fluorophores such as quantum dots will allow arrays of controlled single-photon sources to be fabricated. Such structures also have potential as biological and chemical sensors. ❐

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LIGHT SOURCES

Coloured heat

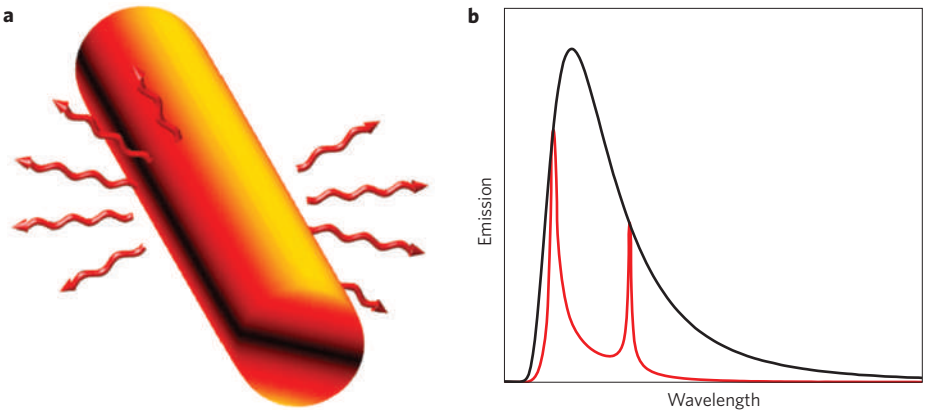
Stanford University researchers have demonstrated the potential of single SiC whiskers to function as narrowband infrared emitters that have controllable emission characteristics.

Rainer Hillenbrand and Javier Aizpurua

The ability to control the frequency, coherence and emission direction of infrared and thermal radiation would be a significant benefit for applications ranging from heat-transfer technology to telecommunications, sensing and spectroscopy. On page 658 of this issue[1], Schuller *et al.* take a step towards this goal by demonstrating how narrowband infrared emission can be achieved with heated silicon carbide (SiC) antennas.

An antenna is a structure or device designed to transmit or receive electromagnetic waves. Radiofrequency antennas have many applications in areas such as radio and television broadcasting, point-to-point radio communication, wireless local area networks, radar, and space exploration. An optical antenna is a device that functions as a receiver and transmitter of visible or infrared light, enabling intriguing applications such as the focusing of light to nanoscale dimensions for ultrahigh-resolution optical and infrared microscopy[2], and single-molecule Raman scattering[3,4]. The transmitting properties of optical antennas can be used, for example, to redirect molecular emission[5]. An optical antenna can be realized by exciting resonant optical modes in micro- and nanostructures[6], with the emission properties determined by its geometry and material properties.

Optical antennas at infrared frequencies are particularly interesting because electromagnetic antenna modes can be excited simply by heating, and the resulting broadband infrared thermal radiation can then be manipulated.



AITZOL GARCÍA-ETXARRI

Figure 1 | Infrared emission mediated by the thermal excitation of electromagnetic antenna modes. **a**, Schematic of the thermal excitation of an antenna with subwavelength-scale diameter. **b**, The resulting narrowband far-field emission spectrum (red curve), compared here with black-body radiation (black curve).

Previous studies involving large extended gratings, photonic crystals and metallic microheaters[7–9] have shown that thermal activation of electromagnetic surface modes can offer control over the coherence, emission direction and spectral properties of thermal emission[7]. Such structures can be considered as thermally excited infrared antennas with emission characteristics that can be tuned by altering the material properties and geometric structures of the surface.

An important goal is the miniaturization of thermal antennas for nanoscale control of heat emission and for the realization of a localized infrared light emitter. The work of Schuller *et al.* in this issue[1], which studies the emission and absorption properties of heated SiC whiskers (single-crystalline rods with a diameter of approximately 1 μm), provides an important contribution to achieving this goal.

By using a Fourier-transform infrared spectrometer equipped with a high-numerical-aperture mirror objective, Schuller *et al.* succeed in measuring both the thermal emission and infrared extinction spectra of a single SiC whisker. SiC exhibits a strong optical phonon response at mid-infrared wavelengths (around 10 μm), giving rise to phonon–polariton resonances in the absorption spectra of subwavelength-scale particles, similar to plasmon resonances in metal nanostructures[2]. Strong dielectric resonances arise near the transverse optical phonon frequency, owing to an exceptionally high refractive index. The results presented by Schuller *et al.* show a strong correlation between infrared absorption and thermal emission peaks, providing clear experimental evidence that the dielectric and phononic resonances are strongly shaping the emission spectrum of the whisker and 'colouring' the heat emitted by the source (a schematic and example spectrum are shown in Fig. 1). This finding also provides a robust experimental demonstration of the fundamental Kirchoff's law, which states that the absorption and emission of a body must be equal. Interestingly, this relation is now shown for a single, subwavelength-scale infrared antenna.

The dielectric and phononic modes governing absorption and emission in this experiment were determined by the material and geometric properties of the SiC whiskers, but in principle any other electromagnetic modes such as plasmonic, waveguide or cavity modes could be used to tune the emission. Dielectric and phonon-based antenna resonances occur in many polar crystals of high technological relevance, such as GaAs or GaN, and thus allow for the development of thermal antennas made from a diverse set of materials. Another interesting possibility is the use of doped semiconductors as antennas. By adjusting the free-carrier density, plasmonic antenna resonances can be tuned over the whole infrared spectral range. Plasmon–phonon coupling in polar semiconductors may be another interesting tuning capability.

The potential to design the thermal emission properties of micro- and nanostructures through dielectric and polaritonic small-particle resonances — demonstrated in this work — promises interesting new perspectives for engineering heat transfer; for example, in thermovoltaic applications, heat isolation or heat-assisted recording. Spectral engineering of thermal sources, such as the ones presented by Schuller *et al.*, may also lead to the development of tiny thermal barcodes and 'smart labels'.

The future prospects of thermal antennas look promising. However, for many practical applications, the limited brightness of the antennas presents a challenge. By properly engineering the antennas, their far-field emission can be maximized, thereby reaching (but not exceeding) the emissivity of a black-body, which is shown theoretically by the authors. This may represent a limitation of the technique for cases when intense infrared signals from localized areas are required, such as in nanoscale chemical sensing or nano-imaging. This black-body limit, however, does not apply to the near-field emission of a body[10]. Close to a resonant thermal antenna — at distances much smaller than one wavelength — strongly enhanced infrared fields can be generated at the emitter surface, owing to the antenna resonances (Fig. 1). The increase of near-field intensity may allow the generation of infrared hot spots for applications in nanoscale heating. These nanoscale infrared fields may also find applications in local chemical sensing or nano-imaging. However, because the black-body emission scales with the emitter size, it will still be challenging to detect the emission that contains the near-field information. The conversion of enhanced near-field thermal emission into efficient far-field signals may therefore be the next 'hot' challenge for thermal antennas. ❐

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