Decoupling of temperature and thermal radiation

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Using thin-film samarium nickel oxide, we show that the well-known relationship between temperature and thermal radiation can be decoupled in a fully passive and reversible way. Our sample features temperature-independent thermally emitted power in the long-wave infrared from 90 to 120 °C, making it promising for camouflage applications.

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The emission of light by hot objects such as lava and incandescent light bulbs is well described by Planck's law and an emissivity term [1]. For objects at human-scale temperatures (e.g., 0 – 200 °C), thermal emission predominately occurs at mid-infrared wavelengths, roughly from 2 to 20 μm. In particular, the 3 – 5 μm and $8-14$ μm windows are significant, since these are regions of atmospheric transparency [2]. Integrating Planck's law over all wavelength and angles within a half sphere yields thermal irradiance as described by the Stefan-Boltzmann law ($I_{tot} = \varepsilon_{tot}\sigma T^4$, where σ is the Stefan-Boltzmann constant, and ε_{tot} is an integrated emissivity). For typical objects, the emissivity is approximately constant, thus temperature is directly related to radiated power. This common relationship enables, e.g., infrared imaging or non-contact thermometry [3]. However, this well-established notion that hotter objects radiate more thermal power can be broken by introducing a spectral emissivity that has a significant temperature dependence [4]. Furthermore, the complete decoupling of temperature and thermal radiation requires a structure with an accurately designed temperature-dependent spectral emissivity such that—as the temperature increases—it completely compensates blackbody radiation. This decoupling can, among other things, be used to conceal information from infrared imaging systems.

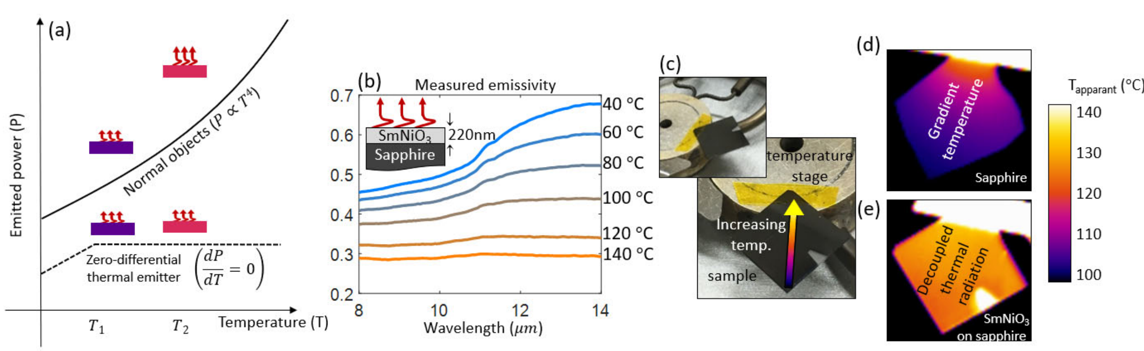

Figure 1: **(a)** For a typical emitter, for example comprising a semiconductor or insulator (cartoon band diagram in (b), top), any change in emission from a temperature-dependent change in materials properties is dwarfed by the T^4 dependence in the Stefan-Boltzmann law. Conversely, a ZDTE decouples temperature and thermal radiation over some temperature range, and thus can only be made from a material with a very strong temperature dependence. **(b)** Measured wavelength- and temperature-dependent emissivity of our ZDTE, comprising a ~220-nm film of $SmNiO_3$ on a sapphire substrate **(c)** visible images of samples hanging from one corner to the heat stage **(d, e)** Long-wave infrared images of two samples with temperature gradients from hot to cold: a sapphire wafer that has a constant emissivity (d) and our and $SmNiO_3$ coating on sapphire that shows uniform thermal radiation (e).

We designed and implemented a structure featuring zero-differential thermal radiation with respect to temperature within the $8-14$ μm atmospheric-transparency window. Our design principle was to passively cancel out the highly temperature-dependent behavior of thermal radiation (as shown by the Stefan-Boltzmann law over all wavelengths) using a temperature-dependent and hysteresis-free spectral emissivity [5]. To achieve this, we used a thin-film structure that incorporates samarium nickel oxide ($SmNiO_3$), a strongly thermochromic material that undergoes a hysteresis-free insulator-to-metal transition (IMT) resulting in a significant change in optical properties from ~40 to 140 ºC [6]. Based on measured complex refractive indices of $SmNiO_3$ and using the transfer-matrix method, we designed a structure that minimized the slope of total thermal radiation versus temperature within the $8 - 14\ \mu$m atmospheric transparent window in the temperature range of 90 to 120 °C. The final structure that we fabricated is comprised of 220-nm-thick $SmNiO_3$ sputtered film on a *c*-plane sapphire substrate. In contrast to many other materials with IMTs (e.g., vanadium dioxide) that have a significant hysteresis, our sample has a completely reversible IMT with essentially no hysteresis. The unique hysteresis-free behavior of our $SmNiO_3$ films was confirmed via electrical resistance measurements and spatially-resolved X-ray absorption spectroscopy (XAS) [5]. This reversible and hysteresis-free behavior is crucial to enable the zero-differential behavior; any hysteresis prevents the cancelation of the blackbody temperature dependence for either heating or cooling or both. To obtain the temperature-dependent spectral emissivity of our sample, we measured its near-normal-incidence reflection spectrum, $R_N(\lambda, T)$, using Fourier transform spectroscopy (FTS). Since the substrate of our sample is opaque in the $8 - 14\ \mu$m range, Kirchhoff's law [7] can be used to calculate the near-normal-incidence emissivity $\varepsilon_N(\lambda, T)$ from the reflection measurements: $\varepsilon_N(\lambda, T) = 1 - R_N(\lambda, T)$ [Fig. 1(b)]. This result is confirmed by directly measuring the thermal emission of the sample and normalizing that to a laboratory blackbody consisting of a vertically-oriented 0.1-mm-tall carbon nanotube forest [5],[8]. By integrating the measured emissivity multiplied by the spectral radiance of a blackbody at the same corresponding temperature, we calculated emitted radiance of our sample which has a similar behavior to zero differential thermal emitter, shown in Fig. 1(a).

To demonstrate the ability of our structure to mask a gradient thermal profile, we captured infrared images of two samples [Fig. 1(b)] using a commercial long-wave infrared camera: the first sample has a typical T^4 dependence (sapphire, Fig. 1(c)) and the second sample is our zero-differential thermal emitter ($SmNiO_3$ on sapphire, Fig. 1(d)). Both samples were mounted to the edge of a heat stage to induce a temperature gradient across the sample. For the sapphire sample, a clear apparent temperature gradient was observed (orange to purple), which correlates to the integrated power detected by the infrared camera. But for our $SmNiO_3$-based sample, the detected temperature appears to be uniform (orange), masking the true thermal gradient of the sample.

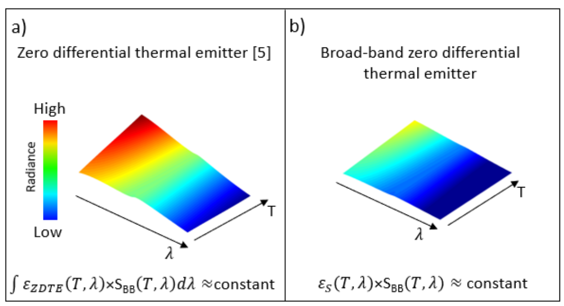

Figure 2: **(a)** temperature- and spectral behavior of zero differential thermal emitter (ZDTE) **(b)** Broad-band ZDTE.

In summary, we showed that it is possible to decouple temperature and thermal radiance by utilizing a hysteresis-free phase-transition material [Fig. 2 (a)]. Our ongoing efforts are aimed at achieving this effect over broader ranges of wavelengths [Fig. 2 (b)] and change the temperature range of decoupling.

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