Professor Forbes and MSc student Lerato Shikwambana, aligning the CO_2 laser for laser-material interaction studies.

A light touch: application of optics and lasers to temperature control problems

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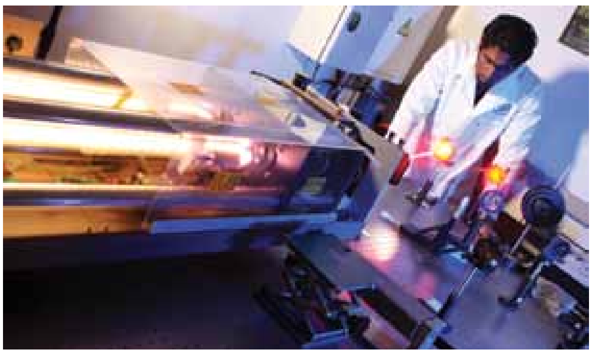
In this article we outline how an all-optical system may be designed for the heating, and then subsequent temperature measurement, of any sample, thus allowing a non-contact approach to thermal studies of materials.

Around one hundred years ago, physicists discovered the nature of blackbodies: objects that exhibit a particular trait that the light they emit is dependent on the temperature of the body itself. The most well known example of a blackbody is our Sun. With a surface temperature of – 6 000 K, the spectrum light from the Sun – its colours. One notes that most of the light is emitted in the ultraviolet and visible parts of the spectrum (wavelengths less than 1 µm), with very little at wavelengths in the infrared (wavelengths greater than 1 µm). The colours one sees are determined only by the temperature of the body, and not by the size or shape of it. This is what makes blackbodies so special, and why we can use the principle to measure temperature.

To create a perfect blackbody, one requires an object that does not reflect or transmit light, but only emits light. You can liken the situation to a box (like a microwave) with a very small aperture. The box allows many different types of waves to oscillate, and they are 'leaked' out through the small aperture. But because the aperture is so small, no other light can get in and then be reflected back out, with the result that only the box determines the type of waves that come out. It turns out that very hot objects also work like this, and a measure of how close they are to the perfect blackbody is the so-called emissivity of the body. If the object has an emissivity of 1, it is a perfect blackbody, whereas most objects we may wish to measure in the laboratory would have a value between 1 and 0. Another property of blackbodies is that as they get hotter, so the intensity of the light that they emit increases. This is known to be proportional to T4, where T is the temperature of the object under study. To illustrate the concept, consider some piece of material that we wish to heat to a particular



MSc student, Malcolm Govender, directs a high power CO_2 laser (left). The laser has a double pass gain volume, seen as two bright tubes, for high power extraction.

After irradiating with a high power laser beam, an industrial diamond sample is severely damaged by the thermal gradients induced in the sample, with both physical and chemical changes evident.

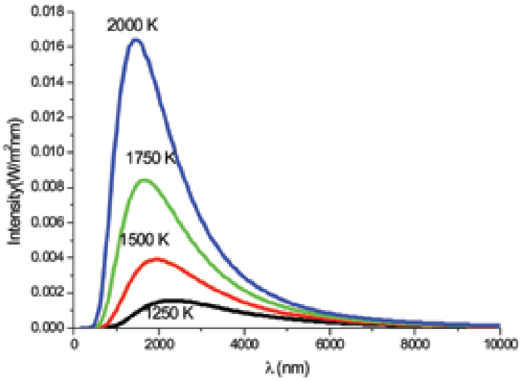
The starting industrial diamond sample is pristine, with a diamond layer on top of a cylindrical base.

- One can use an all-optical approach to measure temperature.
- Laser techniques allow instantaneous temperature measurement across a surface.
- Laser heating of the surface for localised spots holds limitless possibilities.

Take note

temperature: as we make it hotter, so the spectrum (or colours) shifts towards the shorter wavelengths (towards the blue and ultraviolet), while if the material cools down the spectrum shifts towards longer wavelengths (towards the red and infrared). You are most familiar with this when you look at a fire: the hottest part of the flame is at the centre and is blue in colour, while the 'cooler' part of the flame is farther away from the centre and is orange/red in colour. So the old saying 'red hot' should actually be 'blue hot'! This spectrum of light emitted as a function of wavelength (colour) is called the blackbody spectrum, and since it is determined only by the temperature of the object, it can be used to extract very accurate temperature measurements of objects under study if the spectrum itself can be measured. And the good news is that the spectrum can be measured by using standard spectrometers [1] or thermal cameras [2]. In the case of the spectrometer approach, the light from the blackbody is collected, usually in an optical fibre, and directed onto a diffraction grating that splits all the wavelengths up into its spectrum. From this we can deduce the temperature. Thermal cameras work a little differently – they must be calibrated to a known blackbody and base their measurement on the amount of light collected within their detection range (say 4 – 6 μm in wavelength). They are also usually cooled devices, and often very expensive. But nevertheless, we monitor the wavelengths given off by the blackbody, and in particular the amount of light at each wavelength. By fitting the blackbody spectrum to the measured light, we can determine a unique temperature value – the temperature of the object.

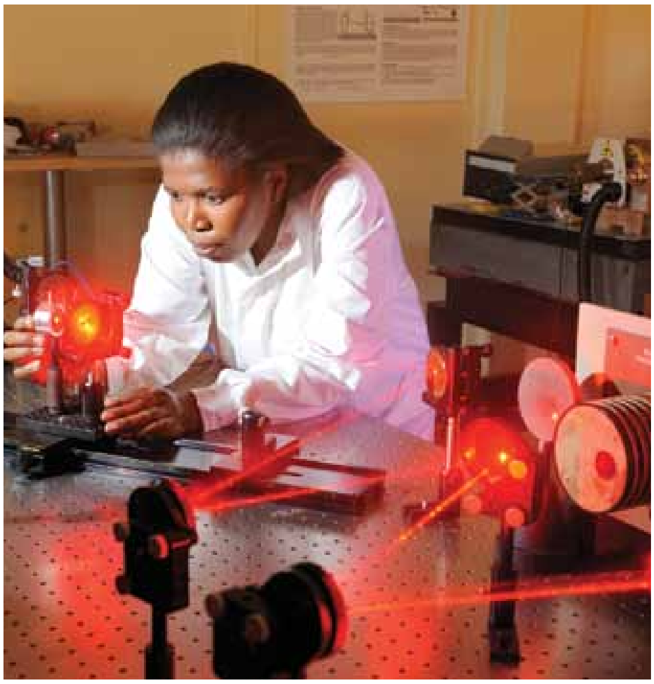
A salient point of this approach is that the object itself is giving off the light of various colours, most of which we cannot see with the eye. Thus the principle of using the blackbody emission is by definition a non-contact measurement process; there is not physical contact with the object under study, and the light we use for our measurement is light that is being 'released' or emitted from the object due to its temperature. Bodies radiate energy when they get hot, and now we may exploit this radiation to extract a precise measurement of the temperature of that body. In typical experiments in our laboratories, we can measure the temperature of a sample to within 1 K from just above room temperature to over 1 000 K, and all the while not coming into contact with the sample.



Typical blackbody spectrums for a range of temperatures. As the temperature of the body increases, so the spectrum shifts towards the blue, or short wavelengths, and the peak intensity of the emitted light increases.

An all-optical approach

One can extend the use of light from measuring the temperature to actually creating the heating in the first place. If laser light is focused onto an absorbing object, then the absorbed light will heat the object. The advantage of laser heating over conventional oven heating is that lasers allow very intense fields to be created in very localised spots on the object, down to just a few micrometres in size. In a typical laser heating and temperature measure experiment in our laser laboratory, we would focus a high power carbon dioxide laser onto



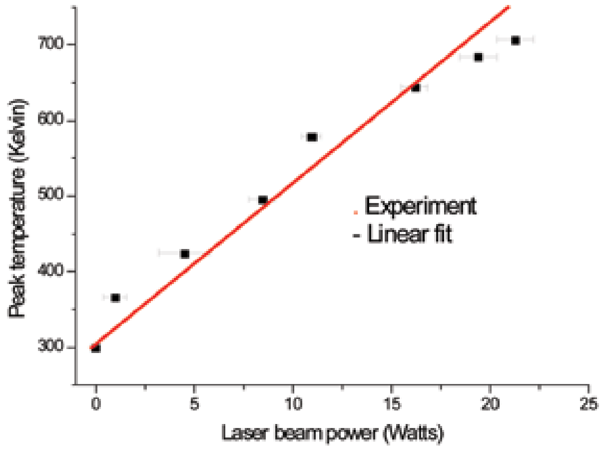
An all optical system for the heating and temperature measurement of samples. Bathusile Masina uses a visible laser (red light) to help direct the invisible infrared light from the high power laser towards the sample to be laser heated. As the sample gets hot, so it radiates as a blackbody, allowing its temperature to be measured.

a sample we wish to study, delivering 30 W of average power in a small spot of less than 1 mm in diameter. As the sample heats up, so the temperature rises until a steady state is reached – that is, when the energy being delivered by the laser matches the energy lost to the surroundings. At any stage in this process we can measure the spectrum of light emitted from the sample, so that we can monitor the temperature rise as a function of time across the whole sample. Thus laser light causes the temperature to rise, and blackbody light allows us to monitor the process – an all-optical temperature control experiment, with no physical contact with the sample! Such a technique can be applied to almost any sample, and has the advantage that the sample can be far away, since the light itself carries the information back to the detector. When high power lasers are used for such heating experiments, it is possible to deliver more than 5 kW of power to the sample in a very focused spot. The intensities reached under these conditions can result in catastrophic damage to the sample under study. The sample after heating is radically altered from that prior to laser heating.

Controlling thermal gradients

One of the questions we would like to answer in our work is whether thermally induced problems in some materials arise as a result of the temperature value itself, ie, how hot the object is, or the thermal gradient introduced due to the object not having the same temperature everywhere. Generally speaking, any heating system will result in a thermal gradient, much like the flame, with some parts hotter than others. If the object is a material of some sort, then stresses are likely to occur as a result of these gradients. So we would like to ask if this damage is due to the very high temperature experienced by the sample, or the very high stressed induced in the sample due to thermal gradients?

We have devised a very simple method to select either one of the two cases: (i) constant temperature across the sample, with no gradient and therefore no stresses, and (ii) a temperature gradient across the sample, with high stresses even at relatively low temperatures. This is achieved by considering how the object will dissipate heat if subjected to a heating source (a laser beam in our case) [3]. There are two very simple methods of holding a sample such that these two cases can be realised in an experiment. First, the sample is held within a well insulated jacket, so that the boundary does not allow any heat flow out from the edges. This means that only radiation is emitted – a very small loss – and so the object very quickly develops a uniform temperature even if the heating mechanism is not uniform across the sample. Alternatively the sample is placed in a copper block that is water cooled, so that the boundary is always at a constant temperature no matter what the heating looks like. Such a scenario results in a very strong thermal gradient across the sample. This type of control is crucial in some applications where one might wish to understand the independent influence of stresses and temperatures, and we are using it to study physical defects in materials due to highly localised heating.



Conclusion

We have developed an all-optical system for the laser heating of samples, and the accurate measurement of the resulting temperature distribution. The technique allows for an instantaneous measurement of the temperature across a surface, and does not require any contact with the system under study. The use of lasers for the heating provides for the localised heating of spots in the micrometer scale, while the power levels available from such lasers are virtually limitless.

References

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[2] http://www.xenics.com/
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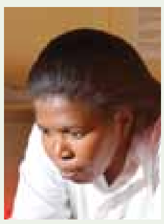

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