Thermal Imaging: Imaging Outside the Law of Reciprocity

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Abstract: Thermal imaging has completely different characteristics from photonic imaging. The difference is not related to the different wavelength typically used (IR vs. visible or UV) but to the fact that the imaging is done outside the domain of the "reciprocity law". This means that the thermal imaging process is controlled by two parameters, energy and power density, while photonic imaging is fully controlled by a single parameter, energy (i.e. exposure) over a surprisingly wide range of power densities (over one billion to one). Adapting visible light imaging architectures to thermal imaging, without considering the need to control power density, severely limits the range of materials that can be used. On the other hand, taking full advantage of this new control parameter opens up a wide range of imaging methods and materials, including inorganic materials, which would have never been considered under the reciprocity law.

Since 1995 there was a shift toward thermal imaging, particularly in CTP. Early thermal materials were also referred to as "IR materials", however it is important to understand that not every IR material is a thermal material and not every thermal material operates in the IR. Thermal materials are characterized by being activated when a threshold temperature is reached. What created the temperature increase is irrelevant: heat, IR laser, visible light laser etc. The only reason for most thermal materials to operate in the IR, particularly 830nm, is the low cost of laser power at this wavelength. Since thermal materials are activated by reaching a threshold temperature rather than an exposure dose, they do not accumulate exposure in the same manner as conventional (photonic) materials. In a conventional material, exposing twice as long with half the power will give the same result as a normal exposure. Exposing for half of the time, pausing and delivering the other half of the exposure will also result in a normal exposure. All this is well known as the "Law of Reciprocity". Exposing a thermal material with half the exposure, pausing and delivering the other half will result in no exposure at all, since the full temperature was not reached in the first half of the exposure and the heat dissipated before the other half was delivered. For the same reasons one cannot boil a cup of water by heating it twice to 50°C instead of heating it once to 100°C. In photonic imaging, such as exposing a film or a printing plate, each photon does some work (modify a molecule) and the most

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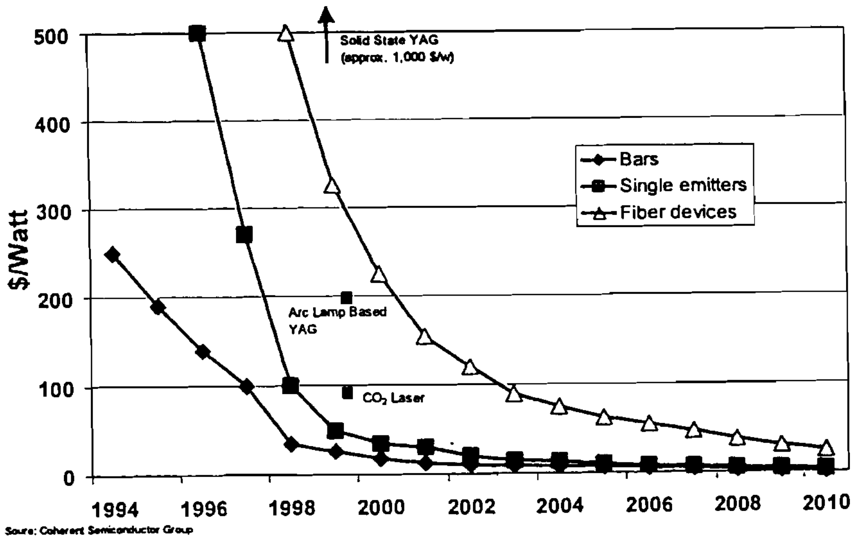
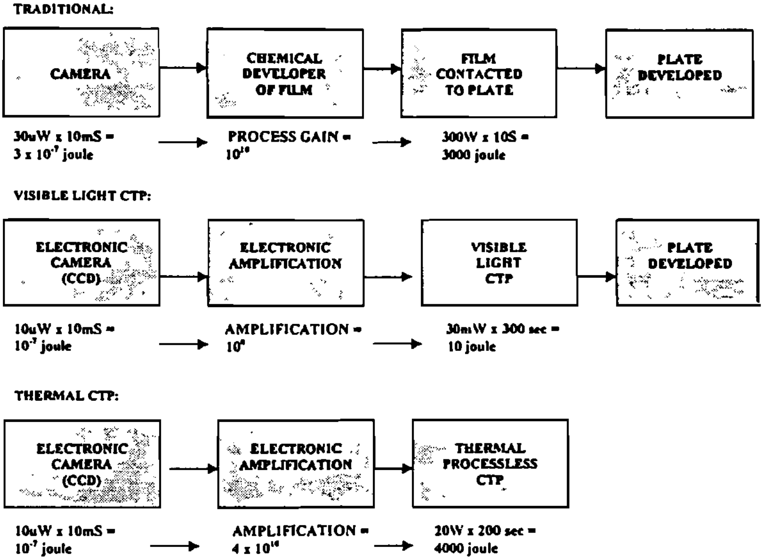
important parameter is the color of the light, which determines the photons energy. If the energy is too low the photon will have no effect. For this reason most conventional imaging in printing was done in the UV, where each photon has more energy. A large number of photons are required to convert all molecules but the rate of the conversion is not important over a very wide range (up to billions). In thermal imaging the color of the light is of no importance (as long as it is absorbed by the material) while the rate is all important, as the heat will escape if photons arrive too slowly. On the other extreme, if photons arrive too fast the material will ablate, which is not desired (unless the material was designed to ablate). In general, ablative materials create debris which has to be vacuumed while imaging. For this reason they are considered less desirable than non-ablative. The most desirable type of materials are those not requiring chemical processing and not requiring ablation. Such materials are starting to emerge and will play a large part starting next year. They are also sometimes referred to as "switchable polymers" as the laser heat is switching them from one property to another (e.g. hydrophilic to hydrophobic for a printing plate). As one cannot generally get something for nothing, most processless materials require more energy than we processed materials. This is not a major issue, as laser power is becoming more affordable with time (see Fig. 1).

Fig.1 Laser Diode Price Trend



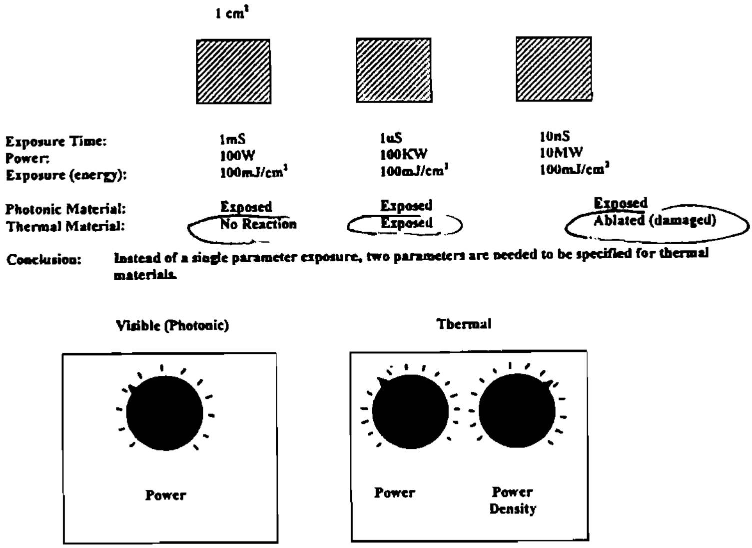
Increasing the chemical gain in a system creates problems with shelf life, pollution, etc. Increasing the electronic gain has no negative effects (as long as the larger lasers are affordable). This is summarized in Fig. 2.

Fig. 2 Evolution of Imaging



The non-reciprocal nature of thermal imaging is shown in Fig. 3.

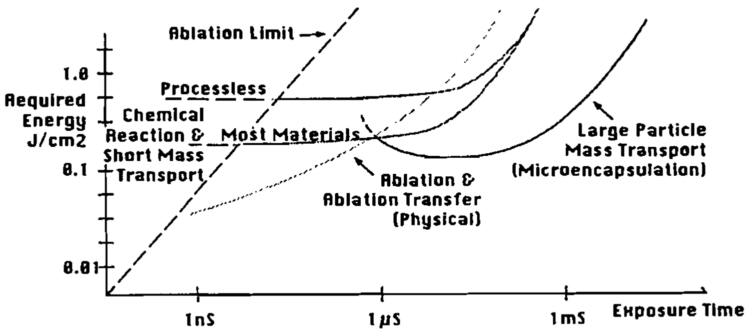
Fig. 3 Imaging Outside the Law of Reciprocity



Understanding the nature of thermal imaging is essential. For example, an out of focus image will create a blurred image on a conventional (photonic) material but will result in no image at all on a thermal material.

Different thermal materials have different power density needs, depending on their principle of operation. Ablative materials prefer high power densities in order to create a sudden explosion and move the ablative material. The majority of the materials used in the printing rely on a chemical reaction. Chemical reactions need both time and temperature and generally follow the well known Arrhenius law. If the energy has to be delivered fast the power density has to be increased (to compensate for the short time). Above a certain power density the material will ablate instead of transforming as designed. This is the main reason why thermal imaging was not successful in internal drum configuration, which provide high power density and short dwell times. Materials based on large mass transport, such as materials based on micro-encapsulation, sometimes require even longer dwell times to allow the molten components to flow. The different optimal exposure times are shown in Fig. 4.

Fig. 4 Types of Thermal Materials

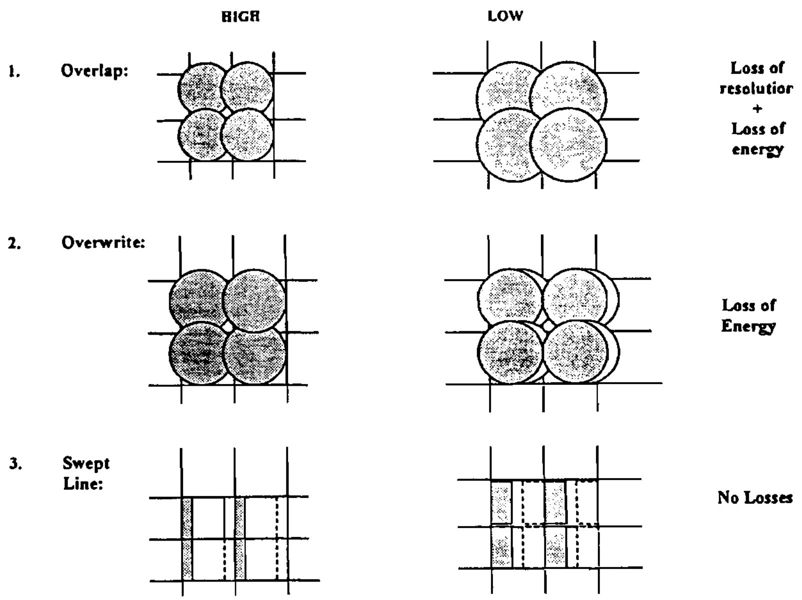


The problem raised by Fig. 4 is that some materials have the same sensitivity but require different power densities. Most thermal materials, such as thermal plates, require energies of 150-300 mJ/cm^2 delivered during a period of 0.5-5uS. If energy is delivered over a longer period most if of it will escape to the substrate, causing loss of sensitivity. Exposures longer than 5uS can also cause loss or resolution due to thermal diffusion. Exposures much shorter than 0.5uS can cause debris from ablation. Such debris will slowly contaminate the machine unless well designed suction systems are used. Most processless thermal materials require 400-800 mJ/cm^2 and therefore are more sensitive to ablation if writing speed is to be maintained (as more power has to be delivered to them during a fixed time, increasing the power density).

For a single material a combination of laser power, spot size and dwell time can be found to operate at the preferred range of energy and power density. The problem arises when the same exposure machine, such as a thermal CTP, has to exposure a wide range of materials. For example, if a CTP machine has to handle proofing materials, films and ablative material as well as regular thermal plates, a wide range of exposure conditions has to be met. If all materials have to be exposed as fast as possible (i.e. using all available laser power) the power setting cannot be used as a parameter, since power will always be set to maximum. This requires a second parameter to be adjustable in order to match the power density to the material being exposed. For example, two materials having the same sensitivity are expected to take the same time to be exposed which dictates the same scan speed. The only degree of freedom left is the power density of the scanning spot.

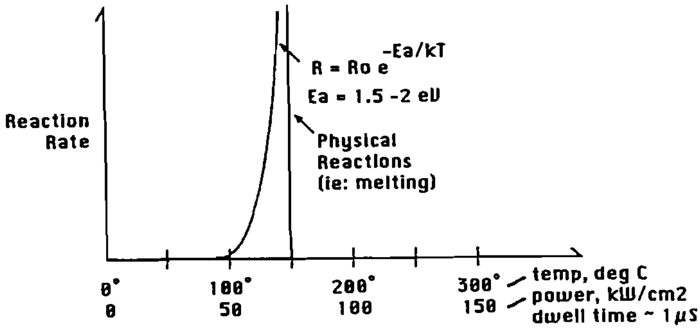
If the material being exposed is ablative it is desired to deliver all the energy at a short time (to increase power density). For material based on chemical reactions it is desired to limit the power density, in order to avoid ablation. Different methods for controlling power density without changing energy are shown in Fig. 5.

Fig. 5 Controlling Power Density



One can always lower power density by lowering the power and scan speed but this causes a comparable loss in throughput. The overlap method in Fig. 5 lowers the power density but also lowers resolution. Also, in thermal materials overlap causes waste of energy because of the non reciprocal nature of thermal imaging. This can be seen from Fig. 6.

Fig. 6 Reaction Rate



Spreading the heat lowers the temperature and greatly reduces the speed of the reaction. A commonly used rule of thumb is changing the reaction speed by a factor of 2 for every 10°C temperature change. While this rule is only accurate for a specific activation energy, it is a good first approximation for thermal materials based on a chemical reaction.

A different approach is imaging each spot multiple times, using multiple laser diodes for each spot. This is shown as "overwriting" in Fig. 5. The disadvantage is loss of sensitivity, as explained earlier. Also, it requires multiple laser diodes for each channel.

The most elegant method to change power density without affecting energy or resolution is creating a spot by scanning a line. This is shown in Fig. 6. By changing the width of the line the power density is changed without affecting other parameters. The disadvantage is that it requires very high optical resolution, as the line is only a fraction of the spot. This can be achieved by the use of an autofocus system and high numerical aperture (NA) optics. Any design for thermal imaging which does not incorporate the ability to change power density independent of energy will be limited in the range of materials it can expose. As new thermal materials, based on a very diverse range of operating principles, are being introduced to the market, the designers of thermal exposure devices should keep this in mind. One should not consider this "reciprocity law failure" as a disadvantage. Once understood, it can be used to great advantage, freeing the designer from all constraints of stray light and interaction between imaged features. Not having to design light tight machines greatly reduces costs and simplifies the design. Use of processless materials removes much of the need for automation and further simplifies the equipment.