Laser Power Handling for DMDs

1 The Challenge

Historically, the primary application of digital micromirror device (DMD) technology has been in display systems, although in the last five years many new applications are being explored by DLP embedded customers. Many of these applications contemplate the use of lasers with DMDs.

Laser applications use continuous and pulsed mode operation. One of the many advantages of pulsed operation is that during the pulse very high peak powers can be reached with relatively low average power consumption. This mode of operation enables various ablation modes (thermal and non-thermal) for deposition, medical and other applications. [(1)]

For lamp (broadband), LED, and continuous laser illumination, steady-state thermal models can be used to predict the temperature of the array and pixels, given the ambient temperature and the optical power spectrum or laser wavelength of the illumination light.

With such models, it is fairly straightforward to determine the limit on the optical illumination power. The limit is determined by the maximum allowable array/pixel temperature. Therefore, for a given set of environmental conditions and optical spectrum, the power limit can be calculated. These limits form in part the basis of the maximum illumination power density specification on DMD data sheets.

However, when considering pulsed laser illumination, the transient temperature of the pixels can no longer be ignored. Large temperature differentials and high temperatures present significant challenges for semiconductor devices that can affect device lifetime. Therefore, it is desirable to keep pixel surface temperature below a critical temperature of 150°C. The effect is often cumulative, so that even if the pixels reach these temperatures for very short periods of time, over many cycles of operation damage may be evidenced. Therefore, a more robust pseudo-transient model is needed to predict the peak transient temperatures of DMD pixels in pulsed laser systems.

With such a model, it then becomes possible to determine a limit on pulsed laser power based on duty cycle, repetition rate (pulse frequency), wavelength, and peak laser power in conjunction with the environmental conditions that a DMD is operating in.

The challenge then is to develop a model that predicts the temperature of a DMD pixel for a given illumination power, wavelength, frequency, and duty cycle (or pulse power/energy, duration, and repetition rate).

2 The Model

The purpose of the model is to predict the peak momentary temperature that the pixels reach during pulsed laser operation. Regardless of the average areal input density, the temperature of individual pixels must remain below 150°C. Above this temperature, it is possible for thermo-chemistry to occur.

The following assumptions are made to simplify the model:

1. The reflectivity of the pixels follows the reflectivity curve of bulk aluminum within the useful range of the device (400 nm–2500 nm).
2. The repetition rate is high enough (> 100 Hz) and the thermal mass of the underlying substrate is large enough (>> thermal mass of the pixel) so that the temperature of the substrate (array) is just the temperature that the array would reach with continuous illumination with the same average power.

(1) Dr. Rüdiger Paschotta, *Pulsed Laser Deposition*, http://www.rp-photonics.com/pulsed_laser_deposition.html (May 2008).

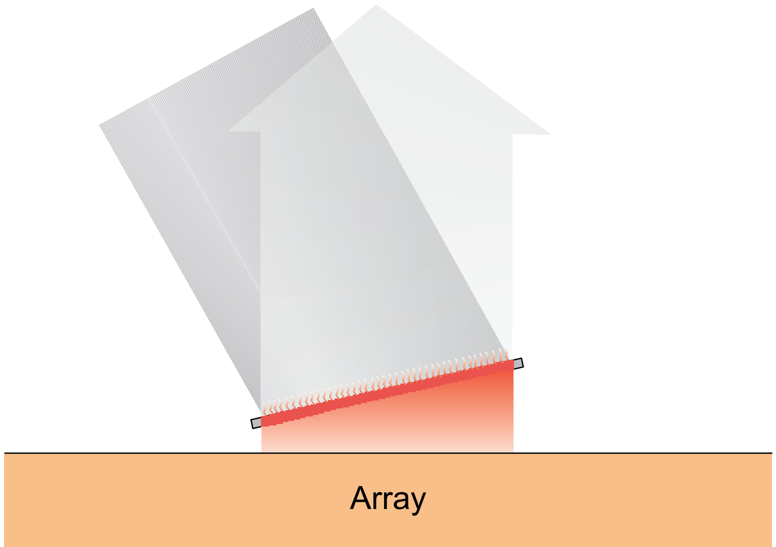

Figure 1. Pixel Heat Transfer to the Array

We will only consider the case where the average areal power is equal to the specified maximum continuous areal power density for a given DMD. Therefore, as the duty cycle varies, the average peak power is given by areal power density$_{avg}$/duty cycle (e.g., 25% duty cycle results in a peak areal power density of 100 W/cm^2).

For this simple model, Equation 1 governs the temperature of the pixel above the array:

$$\Delta T(t) = \Delta T_f - (\Delta T_f - \Delta T_i) \cdot e^{-\alpha \cdot t} \quad (1)$$

where:

ΔT_f is the temperature the pixels would reach as $t \rightarrow \infty$ if the power were applied continuously.

ΔT_I is the initial temperature above the array temperature.

α is the thermal decay constant. It is determined by the thermal conductivity of the pixel to the array divided by the thermal capacity of the pixel.

Let us look at the equation for a minute to see if it makes sense.

- If $\Delta T_I = \Delta T_f$ then it remains at ΔT_f.

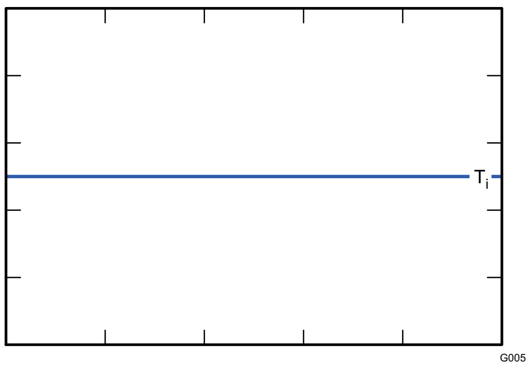

Figure 2.

- If $\Delta T_I > \Delta T_f$ then it decays to ΔT_f exponentially.

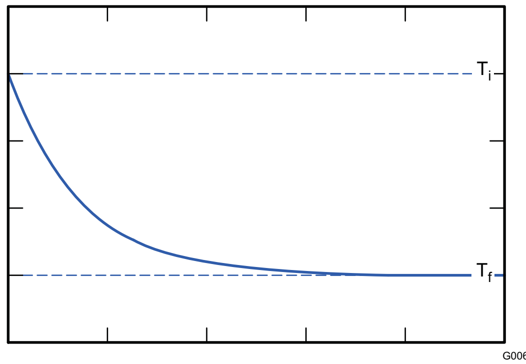

Figure 3.

- If $\Delta T_I < \Delta T_f$ then it approaches ΔT_f asymptotically.

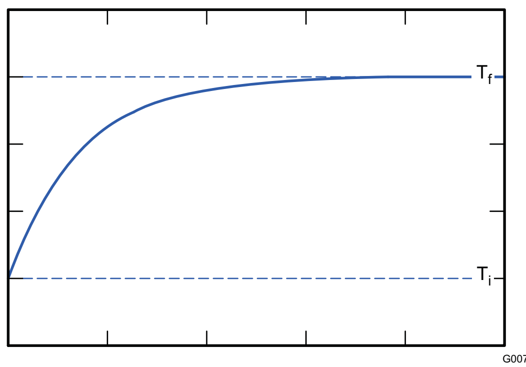

Figure 4.

This is exactly what we expect.

For our model, we want to look at the temperature profile over one pulse cycle. We can break the cycle down into two parts. The first part is when the illumination is on and we are putting in energy at a constant rate. The second part is after the illumination is off and the pixel cools down. Each part has its own T_I and T_f.

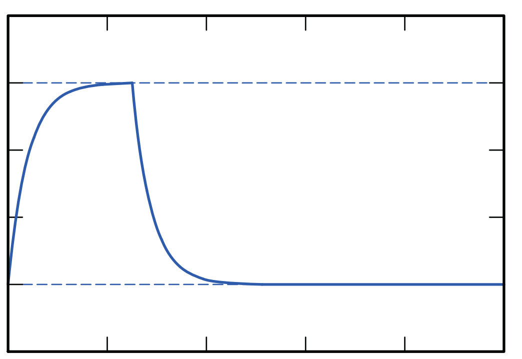

Figure 5.

Now if we assume that $\Delta T_I = 0$ at the beginning of the cycle, we may not end with $\Delta T_{end} = 0$ at the end of a pulse cycle. We are interested in the pseudo-steady state after the system has been up and running. In this state, we require that $\Delta T_I = \Delta T_{end}$. This requires matching the two endpoints, which can be accomplished by calculating iteratively until the difference is smaller than some small delta. The delta chosen for matching in this model is 10^{-10}.

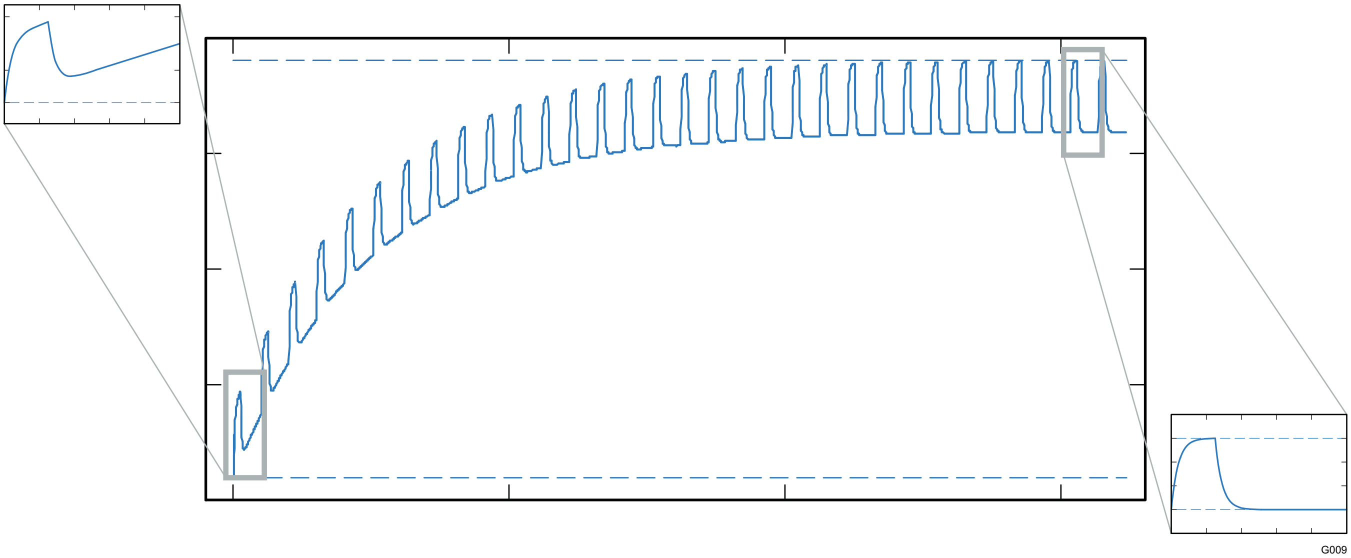

Figure 6.

The specification is 25 W/cm^2 input power in the visible spectrum, where the pixel reflectivity is about 92%, so that about 8% of the energy is absorbed by the pixel surface [(2)] (see Figure 7). For ranges outside the visible spectrum, use the power specification in the data sheet and the absorption for the wavelength being used.

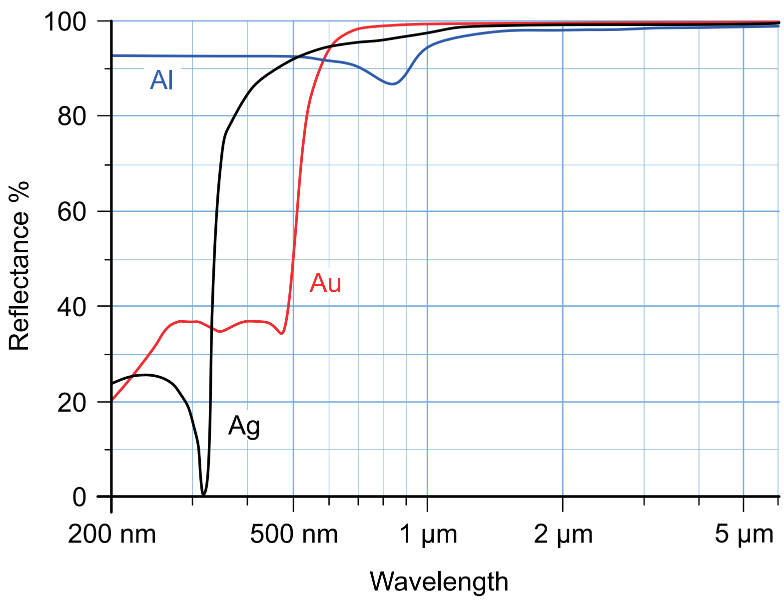

Figure 7. Reflectance vs Wavelength

This part of the model only tells the delta above the array temperature. We must calculate the equivalent array temperature later.

Using the 10.8 µm pixel as an example, Figure 8 shows what happens for 25 W/cm^2 average power and 25% duty cycle as we vary the frequency.

(2) Bob Mellish, *Reflectance vs. wavelength curves for aluminium (Al), silver (Ag), and gold (Au) metal mirrors at normal incidence*, http://en.wikipedia.org/wiki/File:Image-Metal-reflectance.png (November 2005).

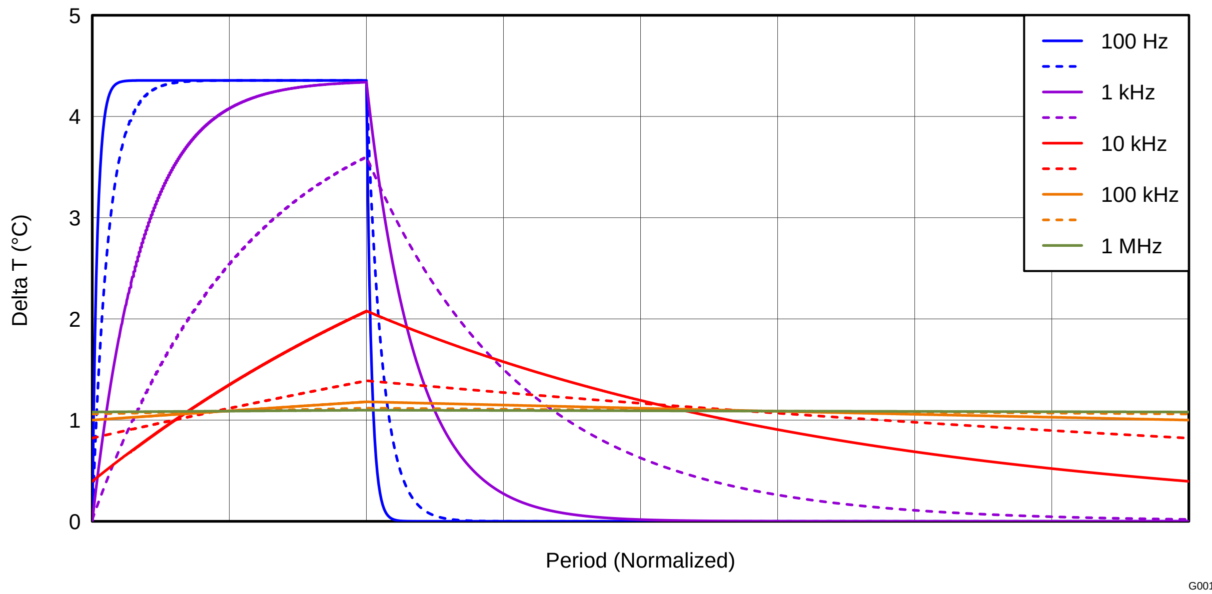

Figure 8. Temperature Over One Cycle for 25% Duty Cycle at Various Frequencies

For 25% duty cycle at 100 Hz, the pulse is long enough that the peak temperature easily reaches the steady state temperature equivalent to 100 W/cm^2 (i.e. Avg_Pwr/Duty_Cycle), whereas at 1 MHz we have essentially reached the same solution as the steady state. This happens because at higher frequencies the energy in each pulse is very small and the pixels do not have time to cool down before more energy is imparted by the next pulse.

For the same pixel size, what happens if we hold the frequency constant and vary the duty cycle?

Remember that the peak power is proportional to 1/duty cycle. The result for three frequencies is shown in Figure 9, Figure 10, and Figure 11.

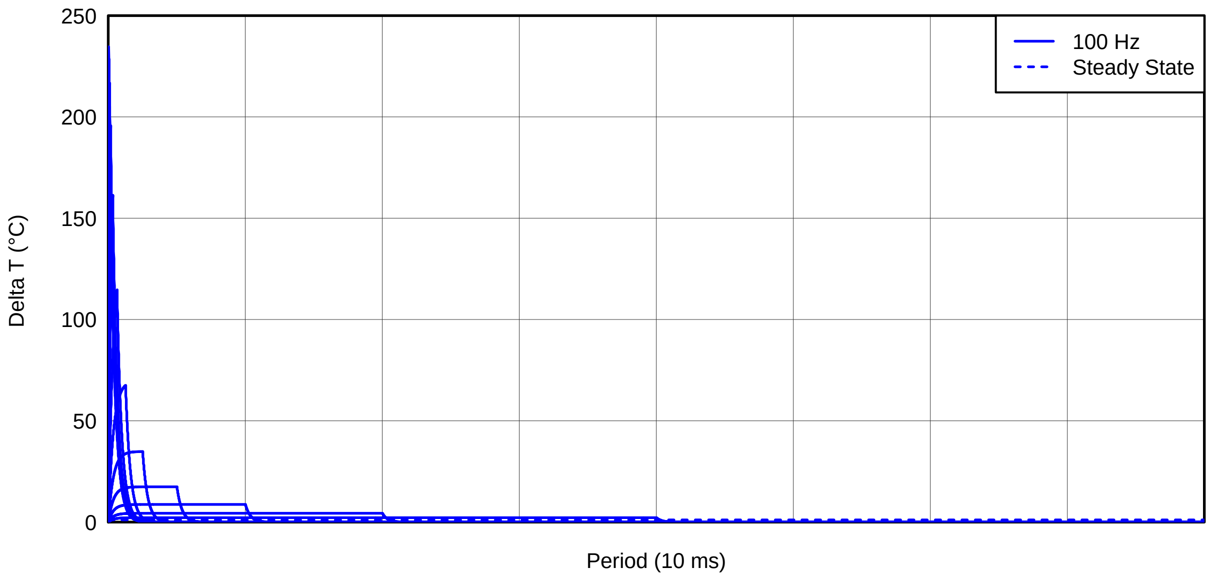

Figure 9. Temperature Over One Cycle for Various Duty Cycles at 100 Hz

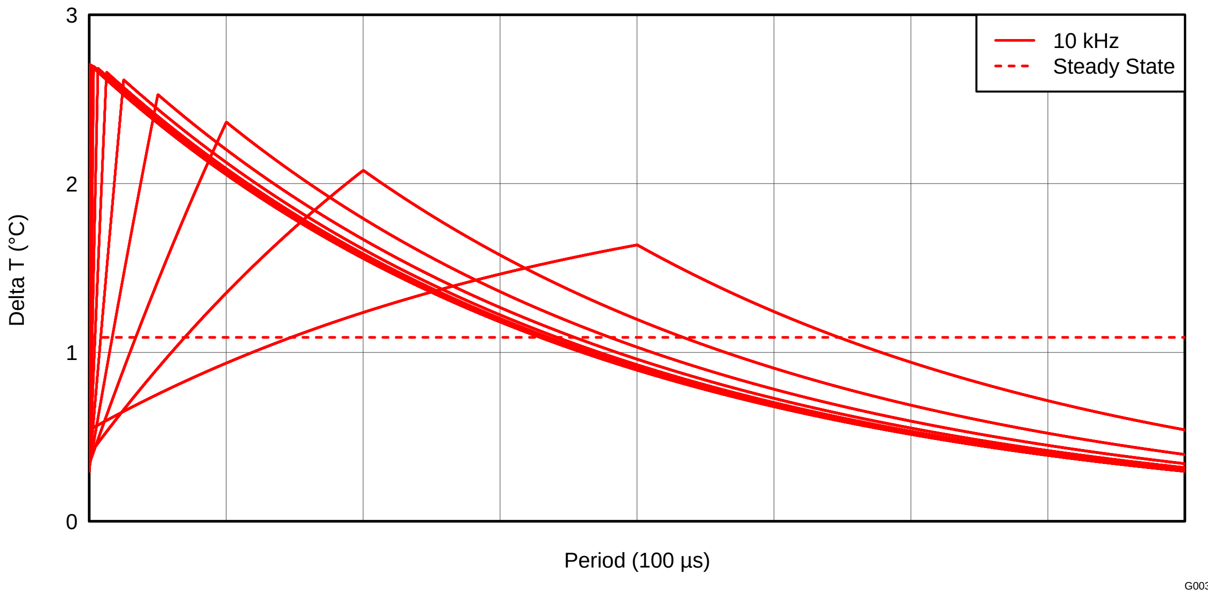

Figure 10. Temperature Over One Cycle for Various Duty Cycles at 10 kHz

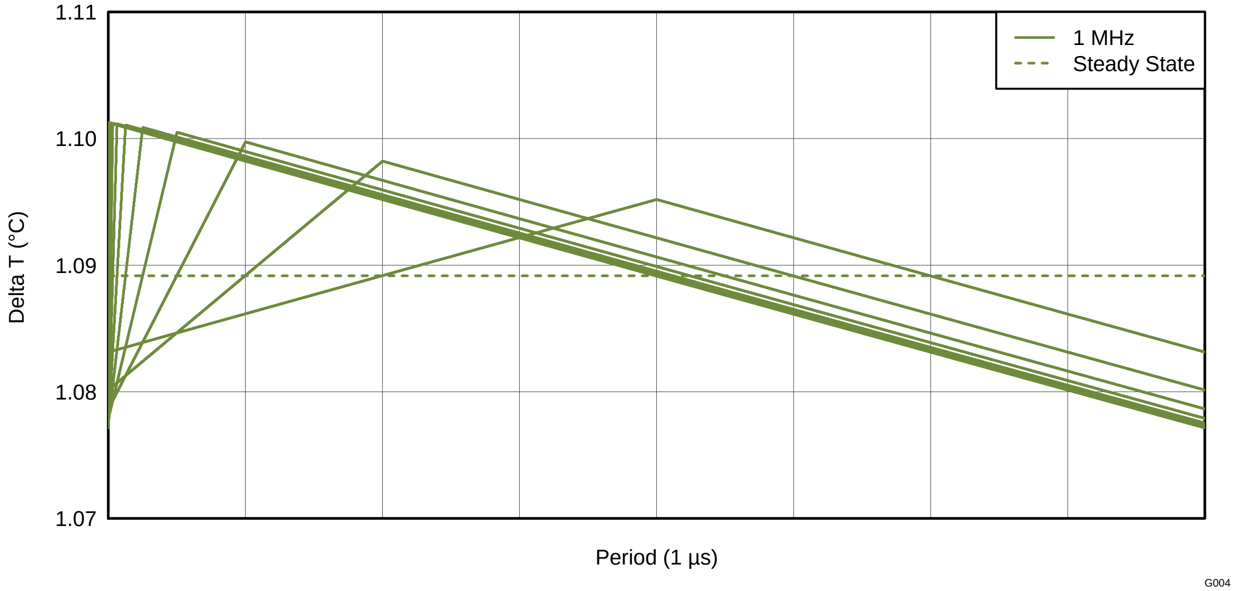

Figure 11. Temperature Over One Cycle for Various Duty Cycles at 1 MHz

We can learn several things from these figures:

1. For lower frequencies, the pulse energies are large enough that the pixels can reach very high temperatures for small duty cycles.
2. For higher frequencies, as the pulse duration decreases, the temperature is dictated by the pulse energy alone. Effectively, there is no appreciable heat transport out of the pixel during the heating phase of the cycle.

We can characterize a critical time for each pixel below which the peak temperature is determined by pulse energy alone. Above this, the peak temperature is limited by the pulse energy / pixel conductivity to the array (i.e., the steady-state equivalent for the peak power).

This value is when the exponential has fallen to $1/e^2$ in Equation 1. This happens when $\alpha \cdot t = 2$. Table 1 shows these times.

Table 1. Critical Time for Different Pixel Sizes

PIXEL SIZE	CRITICAL DURATION
5.4 µm	13 µs
7.56 µm	31 µs
10.8 µm	90 µs
13.68 µm	106 µs

2.1 Array Temperature

The modeling above only predicts the temperature rise above the array temperature. In order to determine the total pixel temperature, we must also know the array temperature.

Array temperature is dependent on the particular package. This varies from about 3–5 degrees above the temperature at the ceramic on the back of the package for 25 W/cm^2 input in the visible spectrum.

Table 2 shows the thermal resistance of the array to the ceramic at the back of the package, the electrical heat load, and the equivalent ΔT for 25 W/cm^2 input for different packages. These values are taken from the respective data sheets.

Table 2. Thermal Resistance, Circuit Heat and Resulting ΔT for 25 W/cm^2 Average Power

PACKAGE	THERMAL RESISTANCE	CIRCUIT HEAT	ΔT ABOVE CERAMIC
0.7-inch (17.78-mm) XGA (A)	0.9°C/W	2 W	11°C
0.95-inch (24.13-mm) 1080p (A)	0.5°C/W	4.4 W	10°C
0.55-inch (13.97-mm) XGA (S450)	0.6°C/W	2 W	5°C
0.17-inch (4.318-mm) HVGA	5°C/W	0.075 W	13°C

These numbers can vary highly, depending on the operating conditions of the pixel (on versus off), illumination angle, and other DMD characteristics such as Darkchip level and any overfill.

2.2 Overall Temperature

Typical consumer projection systems can easily reach 50–55 °C at the ceramic, putting the array temperature in the range of 55–70 °C. The pixel temperature must then be added to this value to evaluate the final peak temperature. Assuming that the array temperature is at 50°C then the ΔT must be kept below 100°C. If an application or system designed results in array temperature lower than 50°C then ΔT can be larger. The critical relationship is shown in Equation 2.

$$T_{array} + \Delta T \leq 150°C_{t} \tag{2}$$

Looking at the devices for three frequencies and two duty cycles, Table 3 shows the pixel peak temperature above the array for 25 W/cm^2 average areal power:

Table 3. Peak Pixel Temperatures for Various Packages Under Various Operating Conditions

ΔT TO ARRAY	100 Hz		1 kHz		10 kHz	
PACKAGE	25% DC (1/4) [2.5 ms pulse]	0.098% DC (1/1024) [9.78 µs pulse]	25% DC (1/4) [250 µs pulse]	0.098% DC (1/1024) [978 ns pulse]	25% DC (1/4) [25 µs pulse]	0.098% DC (1/1024) [97.8 ns pulse]
0.7-inch (17.78-mm) XGA (A)	5.3°C	225°C	5.2°C	24.4°C	2.3°C	3.0°C
0.95-inch (24.13-mm) 1080p (A)	4.4°C	217°C	4.3°C	23.8°C	2.1°C	2.7°C
0.55-inch (13.97-mm) XGA (S450)	4.4°C	217°C	4.3°C	23.8°C	2.1°C	2.7°C

Table 3. Peak Pixel Temperatures for Various Packages Under Various Operating Conditions (continued)

ΔT TO ARRAY	100 Hz		1 kHz		10 kHz	
PACKAGE	25% DC (1/4) [2.5 ms pulse]	0.098% DC (1/1024) [9.78 μs pulse]	25% DC (1/4) [250 μs pulse]	0.098% DC (1/1024) [978 ns pulse]	25% DC (1/4) [25 μs pulse]	0.098% DC (1/1024) [97.8 ns pulse]
0.17-inch (4.318-mm) HVGA	2.6°C	312°C	2.6°C	40.8°C	2.1°C	4.2°C

2.3 Temperature Charts

Figure 12, Figure 13, and Figure 14 show ΔT above the array temperature for an average power density of 25 W/cm^2. For each pulse duration and peak power density, there is a corresponding repetition rate. Exceeding the repetition rate at the same peak power density results in an average power density that exceeds 25 W/cm^2. However, Figure 12, Figure 13, and Figure 14 demonstrate that even for peak power density and pulse durations that do not violate the average power density, there are combinations that exceed ΔT = 150°C – T_{array}.

As an example for the 10.8-μm pixel with 4-kW/cm^2 peak power and a pulse duration of 100 μs at a 60-Hz repetition rate yields an average power of 24 W/cm^2. However, from Chart 6 below, ΔT ≈ 150°C for this peak power and pulse duration, leaving no margin. Therefore, these operational parameters cannot be used.

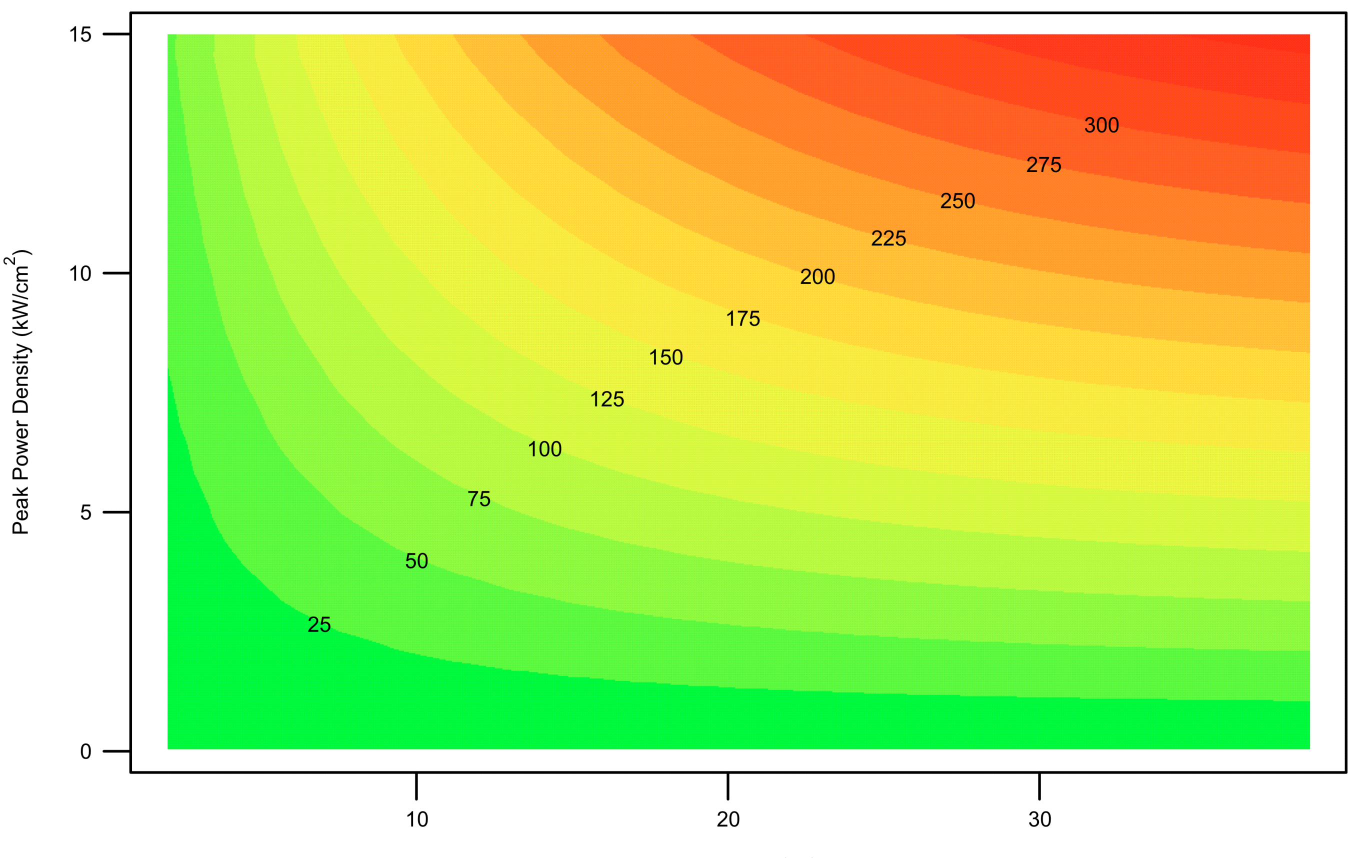

Figure 12. Pixel ΔT for 7.56 μm Pixel

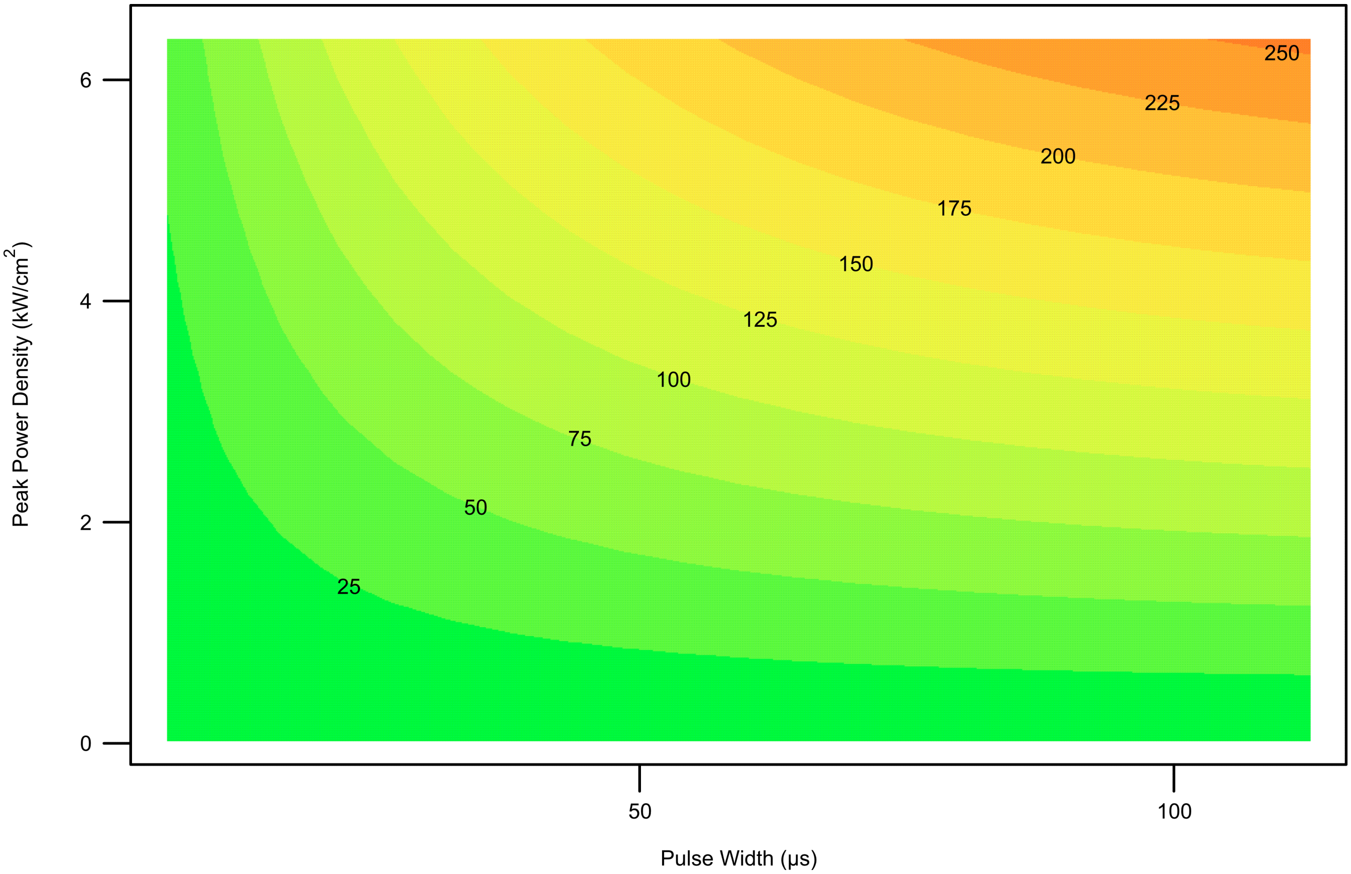

Figure 13. Pixel ΔT for 10.86 µm Pixel

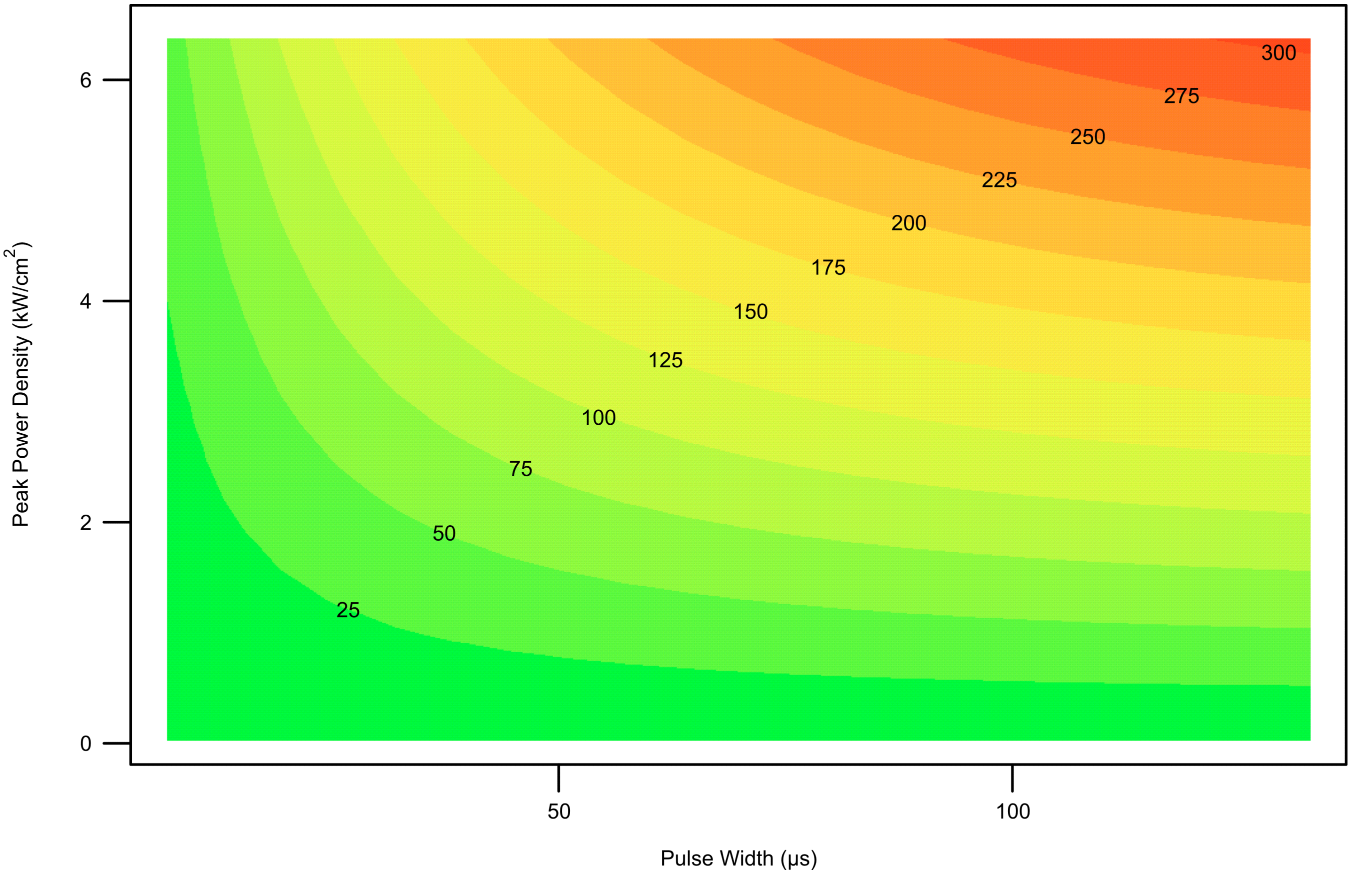

Figure 14. Pixel ΔT for 13.68 μm Pixel

3 Conclusion

This model gives a limit on the pulse energies that can be handled by the DMD for a given pixel type and package.

Therefore, there are two limits we can place with this first level of modeling:

1. The average power density (peak power density • duty cycle) cannot exceed the specification of 25 W/cm^2.
2. If the total pulse energy density delivered instantaneously would cause the pixel to exceed a ΔT_{inst} of (150°C – T_{array}), then the pulse duration must be greater than:

$$Critical\ Width \cdot \frac{\Delta T_{inst}}{150^{\circ}C - T_{array}} \tag{3}$$

   where the value of 100°C can be relaxed if $T_{array} + \Delta T \leq 150°C$ is not violated. So if the array temperature is lower than 50°C, then ΔT can be larger than 100°C.

Using these principles as guidelines helps ensure the prevention of long-term thermal damage to the DMD in a pulsed laser system.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications, notwithstanding any applications-related information or support that may be provided by TI. Further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Mobile Processors	www.ti.com/omap		
Wireless Connectivity	www.ti.com/wirelessconnectivity		
		TI E2E Community Home Page	e2e.ti.com

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265