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Active Cooled 75 to 100 W Equivalent LED Retrofit Bulbs

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Istvan Bakk, Project Manager Light Engines at **Tridonic** and **Brandon Noska**, Applications Engineering Manager at **Nuventix** discuss an active cooled approach to reach 75 W and 100 W incandescent equivalency in warm white LED retrofit bulbs with high CRI and CQS scores as well as a high efficacy above 75 lm/W.

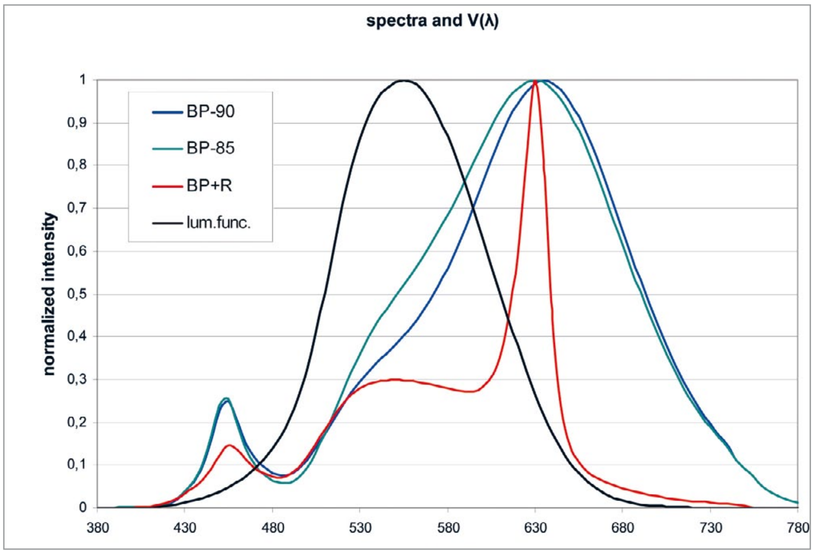


Figure 1: SPD of phosphor only and phosphor-red LED light sources

By the term equivalency of incandescent bulbs we generally understand lm equivalency at much higher efficacy. However customer expectations relate to more equivalency even if it is not exactly drafted:

- Lighting measures: intensity, color temperature, color rendition quality, distribution of light.
- Time dependence: immediate turn on, no warm-up effects, constant light level, flicker is not higher than the incandescent, constancy of measures over lifetime, lifetime 10-50 times higher.
- Size and design: the size, outline should fit the incandescent, having neutral appearance, color, and no observable effects of weight difference.
- Electrical: no sensitivity on numbers of switching, compatibility with existing dimmer, at least 5 times lower power consumption, near resistive load (PF~1.0)
- No noise, no maintenance work, no features to learn
- Fitting to every luminaire [1]
- Price

Engineers getting the above requirements may come up with the idea of an electrically heated tungsten filament. Applying LEDs in the form factor of incandescent bulbs is a challenge, and some compromises have to be made. One thing is clear: the purpose of the bulb is lighting, so the experience of light after retrofitting an incandescent in the room cannot be altered. In the following work we would like to present an approach to reach, and go a bit beyond the equivalency of a 75W and a 100W incandescent bulb. The study relates to a concept prototype leaving enough work for developers to get a product on store shelves.

Light Source Used in the 75 W and 100 W Equivalent Bulbs

Spectral efficacy and performance

The general approach, to reach a color temperature of 2700 K is the application of a yellow and red phosphor blend on the blue die. In Figure 1 the SPD are shown of two such phosphor compositions (YAG + nitride) having CRI 92 and CRI 85 by a blue (BP-90) and green (BP-85) curve respectively. The black curve is the luminosity function [2], showing clearly that a significant portion of the power distribution of such solutions (phosphor only) fall to wavelengths, over 650nm, where the sensitivity of the eye is minute. Having no narrow band red phosphors suitable for such a setup, we have taken a red die instead. The spectrum of the YAG converted blue and red die solution is shown by the red curve (BP+R) on Figure 1. In other words 1 W radiant power of CRI 92, CCT 2700 K light equals to 240 lm by using a phosphor only solution, and 355 lm if we use the phosphor + red die approach. In addition, by converting blue light to red by phosphors, 1/3 of the energy is lost due to the energy difference of the photons (Stokes shift), which is not the case when converting electrical energy to light directly by a red die [3].

Color quality

The impression of the illuminated room should be the same, when an incandescent bulb is replaced by a light-source having a different spectrum. This is difficult to evaluate by measures. It is commonly accepted, that CRI is inadequate to evaluate the color rendering of normal objects and modern pigments [4]. A new measure, CQS, has been developed based on 15 Munsell samples to create a high chroma and span the entire hue circle [5]. The CQS results of the above shown spectra of phosphor only (BP-90, BP-85), the phosphor+red die (BP+R), an incandescent bulb (INC) and a common three-band compact fluorescent lamp (CFL) are shown in Figure 2. To evaluate the visual impression, color preference [6] and color fidelity are found to be important factors [7] to be weighted [8]. Lacking a commonly accepted measure, experts still use live booth experiments [9]. The live experiment results and the CQS evaluation prove that the selected technology (BP+R) is one of the best known candidates to mimic the incandescent spectrum.

Figure 2: **5 blue phosphor + 4 red LED module**

Intensity and efficacy

Modules having the above mentioned spectrum have been built in the prototypes (Figure 2), using 5 blue dice with color conversion material (yellow globe-tops), and 4 red dice (opaque globe-tops). The modules have been built in the standard method: dice are placed on an aluminum-IMS PCB, with dispensed silicone globe-tops.

The average performance data of the modules are shown in Figure 3: lm value and lm/W value in the function of supply current at 25°C heat-sink temperature. The performance depreciation at typical currents (300-600 mA) in the function of temperature is shown on Figure 5 [10].

For the 75 W equivalent (typical 900 lm, 1050 lm in standards) we have taken one module and aimed 1200 lm out of the thermally stable bulb, for the 100 W equivalent (typical 1300 lm, 1521 lm in standards) we have taken two modules and aimed 1700 lm out of the thermally stable bulb. We assume the following parameters: heat-sink temperature to be in the range of 50-75°C, (relates to 10-20% thermal lm de-rating), 5-10% absorption losses on the dome, and 85-90% conversion efficiency of the driver electronics. To reach the aimed lm values and be in the required temperature range, the apparent thermal resistance of the heat-sink (module to ambient) should be in the range of 3 K/W. Having higher temperatures will lead to decreased lm values and color

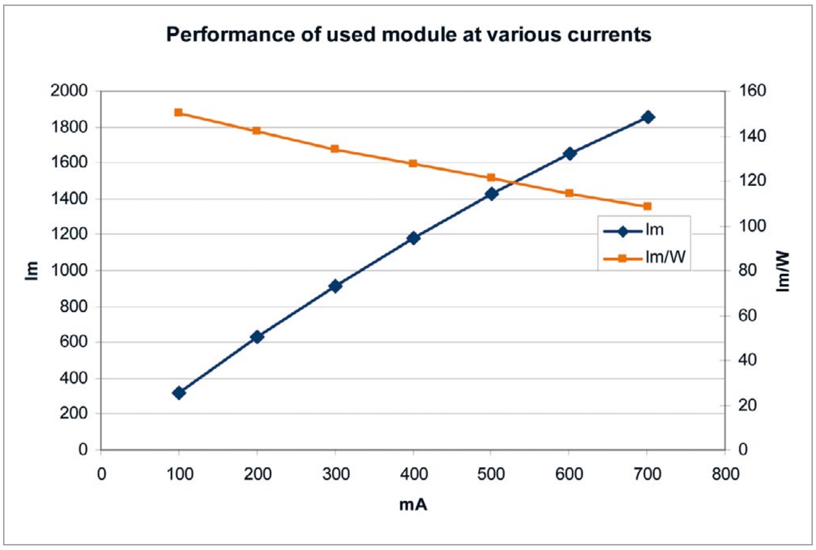


Figure 3: **Luminous flux and efficacy of 5BP+4R**

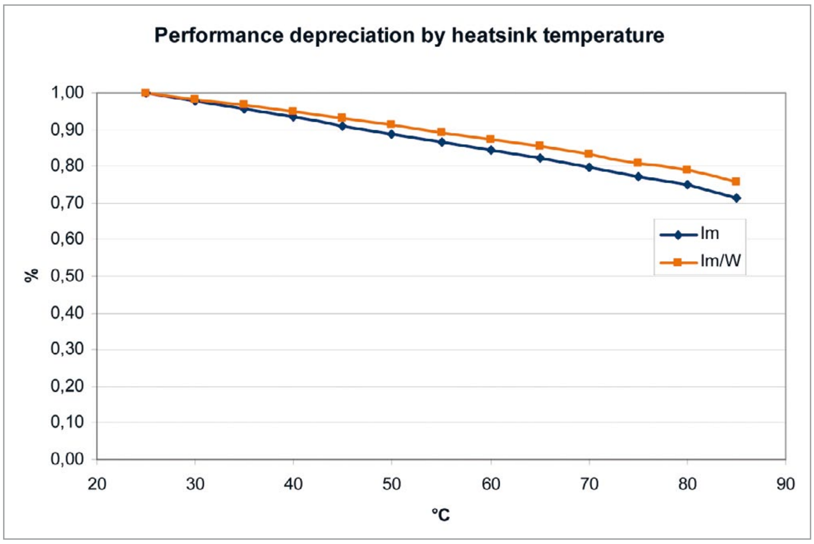


Figure 4: **Thermal de-rating of 5BP+4R**

Test method	Reference colors	BP-90	BP-80	BP+R	INC	CFL
CRI	■■■■■■■■	92	85	92	100	83
CQS	■■■■■■■■■■■■■■■	76	78	92	98	77

Table 1: **CRI and CQS scores of various light sources**

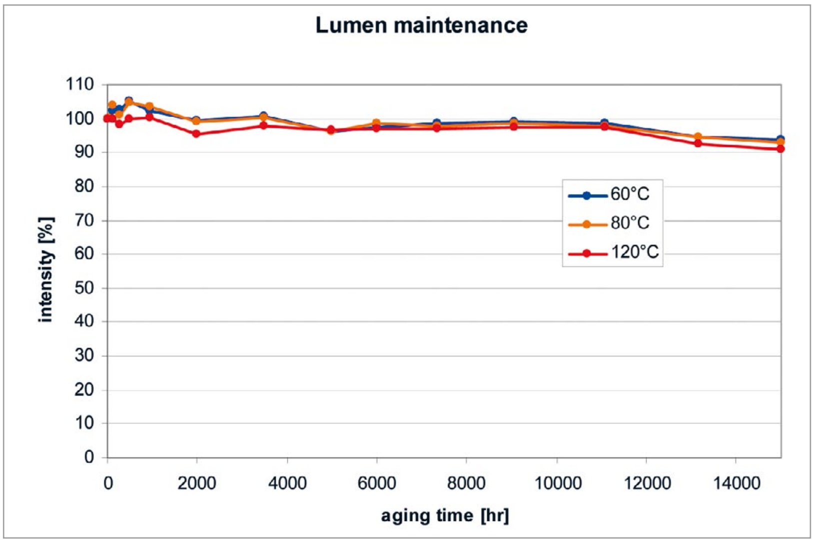


Figure 5: **15 khr lumen maintenance of BP+R modules at various heat-sink temperatures**

temperatures outside the range. On long term the failure rate of the module increases (however the higher probability of failure is in the driver components). It is worth it to mention that according to the long term measurement data of such modules (Figure 5) the lumen maintenance is expected to be within specifications (L70 @ 30 khr) even at elevated temperatures. The lm values at 15 khr are above 90% of the initial values even at 120°C heat-sink temperatures. The chip-on board technology, used at these modules allows having a thermal resistance of 6-8 K/W from junction to heat-sink that presents a very attractive conduction scheme at high powers.

Thermal Solution

The size and shape of retrofit bulbs are defined by existing norms. Looking at the A60 geometry, depending on the passive cooling solution and orientation, a range of 6 ± 1 K/W of apparent system thermal resistance can be realized. Assuming the ambient conditions of 45°C (for example a recessed or not-well-ventilated fixture type), an A60 retrofit lamp would need a system thermal resistance of 3 K/W, thus allowing a Δtheatsink-ambient of 50°C for good performance and reliable operation (F10 @ >30 khr). These conditions cannot be met with a passive heat sink. Such values can't be achieved:

- The Nusselt number is too low for the following reasons: the flow is near laminar, there is poor intermixing between "flow layers" perpendicular to the airflow and the heat transport is diffusion dominated, leading to a high temperature drop at the interface.
- The mass flow rate is low; therefore, the transported heat is too low.

To circumvent these reductions of natural convection, active cooling methods can be selected. In our applications the heat transfer is not limited by the mass flow (heat capacity of air), but the high temperature drop at the heat-sink to air interface (resulting in low Nusselt number). An attractive method, that passes to our requirements are the application of synthetic jets, that create high turbulence on the surface, which increases the Nusselt number, and create a entrained, secondary, airflow directly on the outer surface. Synthetic jets created from electromagnetically driven actuators have no parts in friction, no lubricants to breakdown, and no mechanical wear. Can be operated at low frequencies thus the acoustics are virtually silent. The flow at the actuators is bidirectional, avoiding dust accumulation; however, the resulting flow is directional and turbulent resulting in high heat transfer. The reliability is high, available at low cost and various form factors [10].

Mechanical Setup

The Synthetic jet engine is located in top-side of the bulb (Figure 6). Above the Synthetic jet engine is a heat spreader. This heat spreader has several functions including conducting the heat from the LED module to the finned heat sink, forming nozzles which create synthetic jets and distribute the airflow to the heat sink fins acting as a primary heat exchange with the pumped air. The heat spreader is in good thermal contact with the heat sink surrounding the bulb. For the purposes of this prototype, the heat sink is kept raw, however it can be painted to improve radiative properties. The nozzles above the Synthetic jet engine are radially distributed (Figure 7) at the edge of the

Figure 6: **Cross section of the prototype bulb**

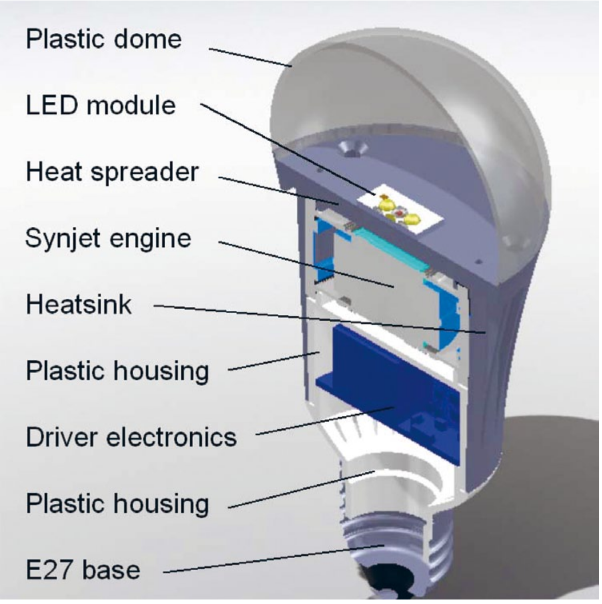
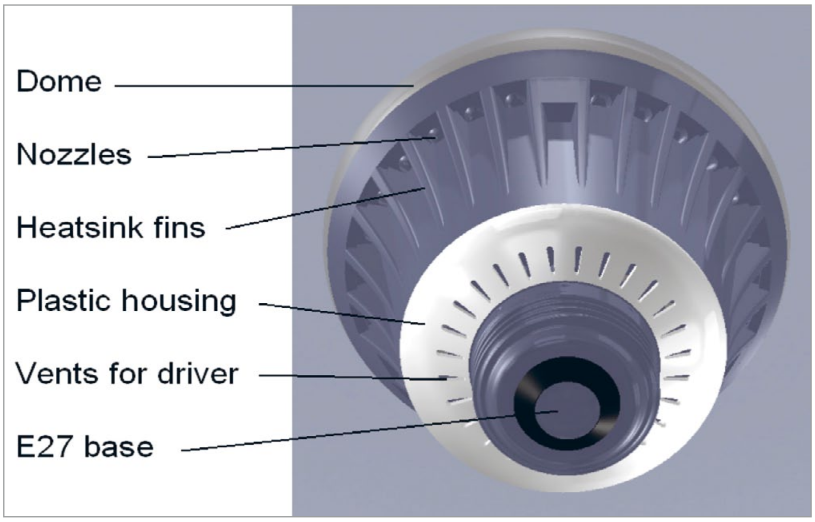


Figure 7: **Bottom view of the prototype bulb**



heat sink, between the fins to allow the synthetic jets to achieve a good heat exchange with ambient air. In order to cool the driver electronics, one chamber of the Synthetic jet engine is connected to the plastic housing of the driver. On the bottom of this housing, vents are opened to allow the exchange of air, thereby cooling the driver electronics.

Active Cooling Process

The active cooling process with the SynJet engine can be divided to two phases, which repeat periodically at a frequency of 40 to 50 Hz. In Phase 1 (as shown in Figure 8) the two membranes expand, increasing the air pressure in the outer chamber and creating an airflow that pushes jets of air through half of the nozzles surrounding the heat sink. The jets drag (entrain), a secondary airflow, from the ambient air, creating a turbulent, high flow stream of air which propagates along the heat sink, towards the base of the bulb. At the same time, the pressure decreases in the inner chamber causing cold air to be sucked in from the top side of the bulb through the second set of nozzles. In phase 2, the opposite process occurs. The membranes contract so air flows to the bulb through the first set of nozzles and synthetic jets are formed on the second set. Since the membranes move in the same phase, but in opposite directions, no vibration or resonance occurs to the bulb. Since the drive frequencies of the membranes are low, the resulting acoustic signature is near silent.

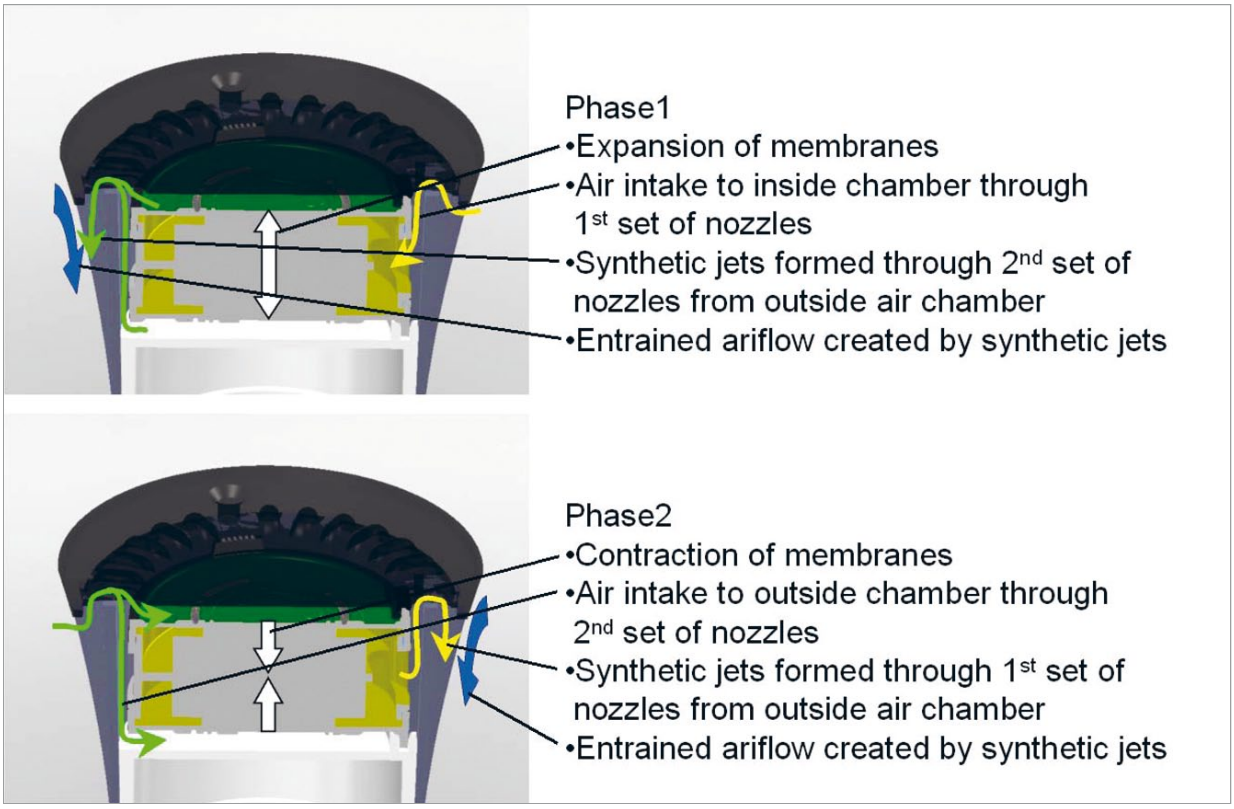
Driver Electronics

The major requirement for electronics is first of all a high conversion efficiency, which reduces the cooling effort to be provided for the driver. The driver should supply the LED string with constant current, while the synthetic jet engine needs constant voltage. Low complexity is preferred for higher reliability, if protection is addressed properly.

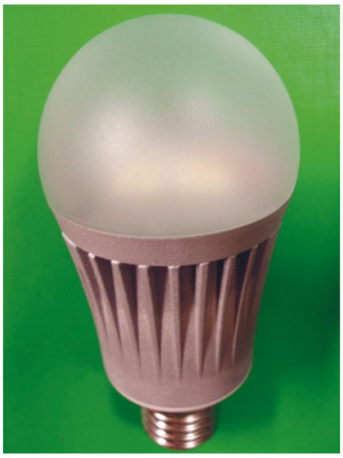
Version	Power consumption of LED	Power consumption of SynJet engine
1200 lm	13.8 W C.C	0.2 W C.V.
1700 lm	17.6 W C.C	0.5 W C.V.

Table 2: **Power consumption of the 75 W and 100 W equivalent LED bulb**

Figure 8: **Jet formation mechanism in the prototype bulb**



A quasi-resonant flyback type converter [12] has been used in primary controlled mode, and isolated topology. A phase-cut dimming feature is implemented in the driver, that has high efficiencies even at dimmed levels (η=0.7 at 10%). The direct dimming mode, and primary control allows a very low list of passive components: for filtering, rectifying, power storage (against ripple), and current setting. This way the size and complexity of the driver is kept low. The supply of the active cooler was solved by a second secondary winding on the transformer. The controller IC addresses the required features of integrated PFC control, over-voltage protection, over-temperature protection, and driver supply voltage protection, LED string open and short protection. The primary control allows a low tolerance set of power control, thus the power of the bulb, and the heat dissipation is controlled in every case. If the active cooling stops for any reason, the controller IC would reach its temperature shut down earlier than the breakdown of any other components (LED string, rectifying diode, transformer), which we have tested in various conditions.



Measure	Version 1	Version 2
Warm white Light Flux	1200 lm	1700 lm
CRI	92	92
CCT	2690 K	2700 K
Electric Power	16 W	21 W
Power Factor	0.94	0.92
LES	75 lm/W	81 lm/W
Noise level	17 dbA	19 dbA
Number of dice	5 blue (white) + 4 red	10 blue (white) + 8 red

Table 3: **Specification of the 75 W and 100 W equivalent LED bulb**

Conclusions

The performance of the bulbs was set to show, that 75 W and 100 W equivalence can easily be reached by the applied module, active cooler and electronics. All values are measured in a temperature stable state, after 60 minutes of warm up at 25°C ambient. It can be seen, that there is a freedom to vary the parameters. For example lumen values of version 2 can be further increased in the system beyond 2000 lm with stable thermal conditions, but an efficacy drops to 75 lm/W. Moreover, noise level can be further decreased by smoothing surfaces; the radiated heat transfer can be increased by painting, just to mention a few measures. Architectural design can be improved a lot, too. However, the aim of this concept study was not to reach the edge values that are enabled by the technology, but to show the industrialization potential of the used components to get real equivalency. ■

Acknowledgement:

The financial support from the Klima- und Energiefonds is gratefully acknowledged.

References:

[1] DIN EN 60630
[2] Eye sensitivity curve at photopic conditions
[3] This is the approach of all XED bulb modules: http://www.tridonic.com/com/en/products/xed.asp
[4] Davis, W. L.; Ohno, Y, Proc. Sixth International LRO Lighting Research Symposium, Orlando, 2006
[5] Not only the sample colours differ, but the test source, colour space and calculation scheme to calculate the difference in colour appearance to correct flaws of CRI: for details see paper in ref.4
[6] It is worth to mention, that colour saturation is preferred, having decreased intensity at the overlap of M and L rod cell sensitivity curves (580 ± 20nm) lead to a more contrasted and saturated colour perception. This effect is used at GE Reveal bulbs, and the BP+R approach.
[7] Other factors as: colour harmony, colour saturation, gamut area scale, and so on could be investigated too, but proper weighing is a challenge
[8] See CIE TC 1-69: "Colour rendition by white light sources"
[9] http://www.ledon-lamp.com/en/ledon_lighting_quality.htm
[10] The separation of lm and lm/W curves is due to the decrease of forward voltage at higher temperatures
[11] The Nuventix SynJet is the only synthetic jet solution for LED cooling, reliability papers and references are available at the company website: www.nuventix.com
[12] www.infineon.com/applications/icl8001g