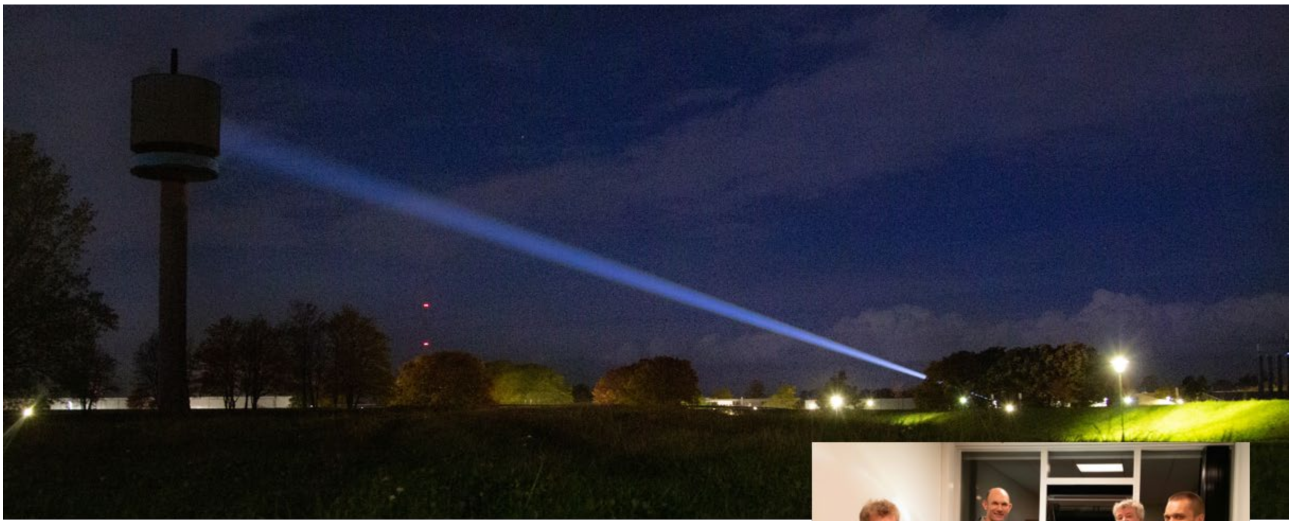
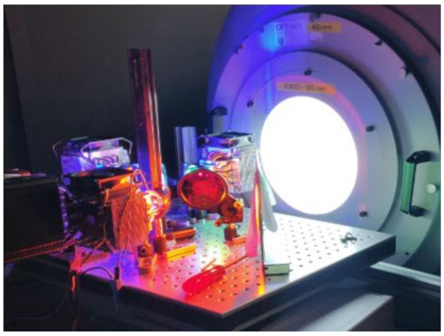
Final report

Energy efficient laser enhancement of stage spotlights

Carsten Dam-Hansen, Anders Thorseth, Ole Bjarlin Jensen, DTU Fotonik and Peter Plesner, BB&S





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1. Project details

Project title	Energy efficient laser enhancement of stage spotlights
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Name of the funding scheme	EUDP 2017-II
Project managing company / institution	DTU Fotonik
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Project partners	Brother, Brother & Sons and Luxtone
Submission date	02 June 2021

2. Summary

The project objective is to bring novel energy efficient laser lighting technology to the entertainment lighting industry by developing and demonstrating two new types of laser based light sources with the goal to replace high power discharge lamps in spot lamps.

Development of new phosphor materials and high-power laser diode systems have led to four prototypes and demonstrators of laser lighting. *Single point LS* with extreme high luminous intensity of 25 mio. cd have been demonstrated and a very high flux unit has been designed and tested. A new *LiV8* color changeable light source for optimization of color quality of laser lighting has demonstrated white light from 3500 to 5000 K with color rendering index of 80. High flux of 16000 lm, and very high luminance of 2130 cd/mm^2 was demonstrated, exceeding LED technology by 20x. A novel *Active Color Management Technology (ACMT)* has been developed for color tunable light sources.

The project has resulted in extensive collaboration on phosphor materials and characterization with Henan Polytechnic University and on laser lighting with University of Toulouse. Collaboration with two internationally leading manufacturers of laser diodes has been established and a signed agreement for use of laser diodes in entertainment lighting is an important result. The results have been disseminated through 7 scientific articles and 12 presentations at seminars and conferences, 3 articles for Danish industry, 2 invited lectures on laser lighting and arrangement of 3 seminars and demonstrations.

The results are already used through implementation of the *ACMT* system in current lighting products, for luminance calibration and will be utilized by bringing new laser white light sources on the entertainment lighting market. Further research in phosphor materials and laser lighting systems will be needed for the energy efficient replacement of high-power discharge lamps. The established collaborations in the project have paved the way for this.

2.1 Danish summary

Projektets mål er at bringe ny energieffektiv laserbelysningsteknologi til underholdningsbelysningsindustrien ved at udvikle og demonstrere to nye typer laserbaserede lyskilder med formålet at kunne erstatte udladningslamper med høj effekt i spotlamper.

Udvikling af nye fosforescerende materialer og kraftige laserdiodesystemer har ført til fire prototyper og demonstratorer af laserbelysning. *Single point LS* med ekstrem høj lysstyrke på 25 mio. cd er blevet demonstreret og en meget høj flux-enhed er designet og testet. En ny *LiV8* farveskiftende lyskilde til optimering af farvekvaliteten af laserbelysning har demonstreret hvidt lys fra 3500 til 5000 K med farvegengivelsesindeks på 80. Der blev demonstreret høj flux på 16000 lm og en meget høj luminans på 2130 cd/mm^2, der overstiger LED-teknologien med 20x. En ny *Active Color Management Technology* (*ACMT*) er blevet udviklet og implementeret i produktion og kalibrering af farveskiftende lyskilder.

Projektet har resulteret i et omfattende samarbejde om fosforescerende materialer og karakterisering med Henan Polytechnic University og om laserbelysning med University of Toulouse. Samarbejde med to internationalt førende producenter af laserdioder er etableret, og en underskrevet aftale om brug af laserdioder i underholdningsbelysning er et vigtigt resultat. Resultaterne er formidlet gennem 7 videnskabelige artikler og 12 præsentationer på seminarer og konferencer, 3 artikler til dansk industri, 2 inviterede foredrag om laserbelysning og 3 arrangementer som seminarer og demonstrationer.

Resultaterne bruges allerede gennem implementering af *ACMT*-systemet i nuværende belysningsprodukter, som luminans kalibrerings lyskilde og vil derudover bruges ved at bringe nye laserhvide lyskilder på markedet for underholdningsbelysning. Yderligere forskning af materialer og laserbelysningssystemer er nødvendig for den energieffektive udskiftning af høj-effekts udladningslamper. De etablerede samarbejder i projektet har banet vejen for dette.

3. Project objectives

The project objective was bringing novel energy efficient laser lighting technology to the entertainment lighting industry by developing and demonstrating two new types of laser based light sources. They are to be used for replacement of high power discharge lamps in stage spot lamps and provide higher efficiency, longer lifetime and reduced environmental impact. The two novel types of laser based light engines were:

- *Single point LS*: pure laser based light engine
- *LiV8*: combined laser and LED based light engine for optimized color rendering and color control

Both should be demonstrated as replacements of HID lamps in high power spot lamp fixtures. The Single point LS was expected to reach manufacturing of a first pre-production series. This included achieving good results in the activities below.

- Development of high power focusable blue diode laser systems in excess of 150 W
- Development and test of substrates/bonding for phosphor materials capable of handling high laser power densities and provide energy efficient conversion
- Development and optimization of optical systems for laser light engines delivering 30.000 lm
- Thermal, mechanical and electronic design of light engines
- Optimization of color quality and control with laser/LED color mixing
- Market analysis and business development

The energy technology targeted in this project is solid state lighting. The project has developed application ready demonstrator models of high luminance solid state laser based light sources. The competing technologies are the traditional arch (HID) lamps which gives high luminance and LED which gives high efficiency and lifetime. However, laser based lighting products have been developed that exceed arch based light sources in terms of usability, controllability and expected lifetime, and outperforms LED in terms of luminance, beam shaping and directionality.

4. Project implementation

The project has to a large extent followed the project plan that was setup in the application with deliveries and milestones. The project was divided into seven work packages (WP) with each their WP leader. These are briefly described with the deliveries and milestones associated with each WP below:

WP 1 Project management led by Carsten Dam-Hansen, DTU

Has established and run project and steering group meetings, provided economic reports every half year, yearly progress reports, and this final project report.

WP 2 Laser systems led by Ole Bjarlin Jensen, DTU

Has developed and tested blue laser diode systems, has provided high beam quality blue laser system for the test and characterisation of phosphor materials in WP3 and a high power blue laser diode system for WP4, capable of delivering 450 W of power.

WP 3 Wavelength converters led by Ole Bjarlin Jensen, DTU

Development of specialized phosphors in the beginning by Luxtone, and later In a large extent by Henan Poytechninc University. Has provided setup facilities for experimental material characterization and synthesized phosphor materials for WP4. As a milestone scientific papers on phosphor material characterization has been published and a library of material parameters for computer models.

WP 4 Light engine development led by Carsten Dam-Hansen, DTU

Has developed computer models of laser/LED lighting systems, and experimental test on laser based light engines. As a milestone articles on laser-based lighting systems have been published. 3D optical designs of components and systems for single point LS and the LiV8 has been delivered for product design in WP7.

WP 5 Color control and quality led by Anders Thorseth, DTU

Has developed setup of color control concept for short and long term color stability investigation, has provided photometric testing and test reports for single point LS and LiV8 for WP6 and developed a working color control and management system (ACMT).

WP 6 Laser light engine market led by Peter Plesner, BB&S

Has worked on market strategy/business plan development, with product specifications as milestones, product demonstrations at trade shows has been hindered by the corona situation, but replaced by online seminars and events.

WP 7 Laser light engine technical system led by Christian Poulsen for BB&S

Has developed driver electronics, optics, mechanical and thermal design of single point LS and LiV8, and has delivered two functional Single point LS prototypes and one functional LiV8 prototype for demonstration. Implementation of ACMT color control system for calibration and control of color changing fixtures. As a milestone a first pre-production unit of a high intensity Single point LS has been ordered.

There was large interest in the project from outside Denmark. This has led to a French Danish collaboration on laser lighting that has been established between DTU Fotonik and the University of Toulouse, France.

Carsten Dam-Hansen has visited the university and was examiner for Ph.D. student Ada Czesnakowska for a project on laser lighting, and Professor Georges Zissis visited DTU Fotonik as examiner for Ph.D. student Anastasiia Krasnoshchoka for a project also on laser lighting. The latter project was a DTU financed Ph.D. project and interaction between the projects have resulted in better result and more scientific publications.

In the beginning of the project Luxtone was responsible for phosphor materials and substrates. One of the first publications DTU made on laser lighting gained large interest and resulted in guest researcher Xu Jian from Henan Polytechnic University from China, visiting DTU Fotonik for 9 months from June 2018. This has been and is continuing to be a strong collaboration on the investigation of phosphor material development and characterization properties for laser lighting and has boosted the number of scientific articles within the project.

There were both market and technology related risks associated with the project that might have hindered the completion of the project. The availability of high power blue laser diodes and arrays from the two main producers, Osram and Nichia, was almost non-existing in the beginning of the project. In the first part of the project it was not possible to buy laser components from the producers. It was necessary to buy them second hand, e.g. through E-bay, and hence it was difficult to get the best and most efficient laser diode arrays. And it would be impossible to initiate a production of laser based light engines if you cannot buy laser arrays from the producers. Peter Plesner, BB&S, has taken discussion of possible volume sales and need for samples with the producers of laser diodes. This resulted halfway into the project period in a contact to the Product Manager on Laser Diodes at Nichia Europe B.V. An NDA was negotiated and will paved the ground for information exchange on new products and the purchase of samples for the research and development work. This was regarded as a major breakthrough and removal or reduction of the market risk in being able to buy laser diode components for production of laser based light engines. Ole Bjarlin Jensen, DTU, has made contact with Kyocera SLD Laser, and this has resulted in purchase of white light laser based components for new laser lighting systems and a fibre based laser source for enhanced material characterisation.

Another less serious but important risk is the reluctance from users against laser based lighting, due to believed danger from blue lasers. It may be difficult to convince users to employ laser based lighting and hence to putting these new products on the market. In order to overcome this, demonstrations of laser based lighting for potential users will have to be carried out along with information for user. This has been done at the arranged seminars and events, which however has been limited due to the corona/Covid-19 situation.

There is small risk is that the phosphor materials will not be able to withstand the high power densities needed to replace the highest power HID lamps. This will not affect the main idea in the project, but it may reduce the achievable light out-put and the range of HID lamp powers that can be replaced. It was the purpose of WP3 to find the optimum phosphor material with regard to efficiency and saturation, and the best available has been used in the laser based light engines. It has been shown that the temperature of the material is crucial and efficient heat management is very important. Have gotten contact to Schott Advanced Optics who are a leading manufacturer of phosphor materials for laser based lighting. An agreement with phosphor samples has been done. Even with the best available phosphor materials and efficient cooling, the project has shown that homogeneous laser illumination is required to obtain the highest light emission.

The Corona/Covid-19 situation was an unexpected problem and had a heavy influence on the project. especially during the first months of the lockdown period. Closed laboratories, lack of component delivery, general upheaval of the entertainment lighting market etc. meant that the project management decided to apply for an extension of the project. A 6 month extension of the project was granted and a change in budget due to the limitations in travel due to Corona/Covid-19 restrictions. It has had the consequence that scientific conferences and trade shows have been cancelled and it has not been possible to travel in the extent that was planned.

5. Project results

The original objective of the project has been substantially obtained. The project has produced a number of technological results with good results on laser lighting components, systems and color adjustment. The main obtained technological results are summarized below and described in more details in the following sections.

- 25 million cd *Single Point LS* light engine demonstrated.
- *LiV8* Color changeable light system demonstrator with 16.000 lm output and possibility to change the correlated color temperature (CCT) and maintain high color rendering index (CRI) of 80.
- Novel *Single Point LS* with 12.000 lm output limited by thermal effects in the phosphor. This includes optical system for combining the light from 6 laser arrays at the phosphor.
- Development of phosphor materials with improved thermal handling, efficiency, color quality and light confinement.
- Setups for characterization of phosphor materials.
- *Active Color Management Technology* (ACMT) system for automatic color adjustment in lamps. This system is now implemented in BB&S's products.

5.1 Laser systems

Blue diode lasers based on single emitters and laser arrays have been investigated as possible sources for use in laser lighting. Single emitter laser diodes have been purchased from different vendors and output powers reaching 6 W has been obtained. In the project, testing of phosphor materials was critical and a setup for automated characterization of phosphors was developed.

Arrays using 8 of such single emitter diode lasers were tested. The output power was slightly lower than for 8 individual emitters but the main challenge with these arrays were the angular deviation between the emitters and the divergence of the emitters. This would cause serious challenges when combining lasers and focusing to a small area on the phosphors.

Laser arrays with more and more closely spaced emitters became available through the project and through our good relations to one of the main manufacturers of laser diodes, we have access to the newest developments in the field. Laser arrays with up to 24 emitters were tested. The output power for such an array is shown in Figure 1, where it can be seen that more than 90 W is available and this is limited by the current range of the used power supply. Furthermore, the angular deviation was measured and found to be very good. This laser array was chosen for the LiV8 color changeable laser light engine, described in 5.4. In order to reach even higher luminous flux and luminance, combining laser arrays is a possibility, which was explored in the single point light source, described in 5.3.1. Here, six arrays with 14 emitters each were combined on a single phosphor material. Each array is capable of emitting 75 W laser light giving a total laser power of 450 W. The 14 emitter arrays were chosen because of their rectangular geometry enabling combining in the mechanical and optical solution chosen for the light source.

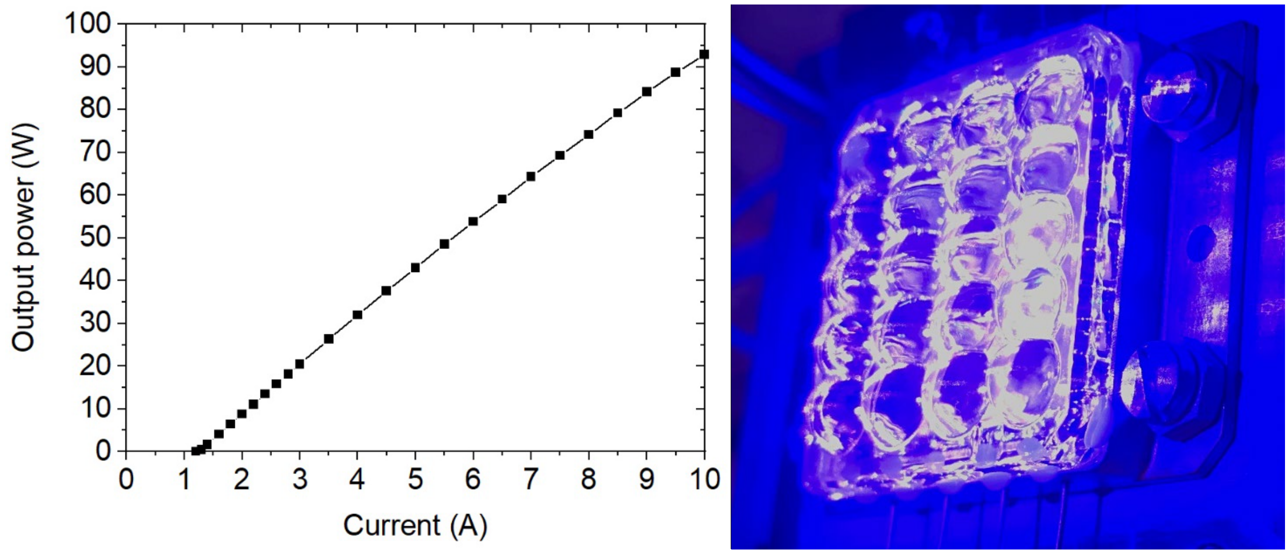


Figure 1. Output power from a laser array with 24 emitters as a function of the electrical current (left) and an image of the laser array in operation (right).

5.2 Phosphor material characteristics

Several new phosphor materials have been developed and tested during the project. The main parameters for phosphors for laser lighting are the efficiency, generated spectrum, thermal properties and saturation properties. Standard LED phosphors are not applicable in laser lighting due to the very high power density on the phosphor. Standard LED phosphors will be damaged. Therefore, a new class of phosphor materials is developed for laser lighting. This includes, single crystal phosphors, ceramic phosphors, phosphors in glass and glass composite phosphors. We have tested several different phosphor materials both commercially available and newly developed materials and a catalog of the materials have been made. In general many materials are promising for laser lighting but for the applications in this project, we have chosen to use ceramic phosphor materials as they are the best compromise between high efficiency, good thermal properties and adequate scattering properties making the light emitted homogeneous. The main downside is the challenge of making ceramic phosphors with excellent colorimetric properties. In general, the tested ceramic phosphors are all based on a single phosphor component limiting the CCT to approximately 6000 K and CRI of less than 70. The luminous efficacy of the phosphors depend on the exact fabrication method, the concentration of phosphor in the ceramic, the losses in the materials as well as the thickness of the phosphors. Generally, the efficacy of the tested phosphors is in the range 100-250 lm/W and somewhat dependent on the laser power density. The materials used in the final demonstrations are 100-150 μm thick ceramic phosphors bonded to a heat spreader for good thermal handling. They have high efficacy of approximately 250 lm/W.

Through the project, an extensive catalog of phosphor materials has been established. More than 100 different phosphors are listed in the catalog, which contains materials based on single crystals, transparent ceramic phosphors, composite ceramic phosphors, phosphor in glass, glass composites and quantum dots. Many of these phosphors are characterized in terms of efficiency and colorimetric properties, while a selection has been characterized in terms of confinement of the light spot.

5.2.1 Material characterization setup

A new automated spectroradiometric characterization setup for phosphor materials with double integrating spheres for both spectral reflection and transmission measurement of converted light was developed. Two excitation lasers at 450 nm or 405 nm can be used with adjustable power and spot size yielding a large range of laser power densities from 0 to 400 W/mm^2 on the phosphor material. This setup has been recently updated with a 20 W fibre coupled laser source capable of achieving a more well-defined circular spot at high power densities.

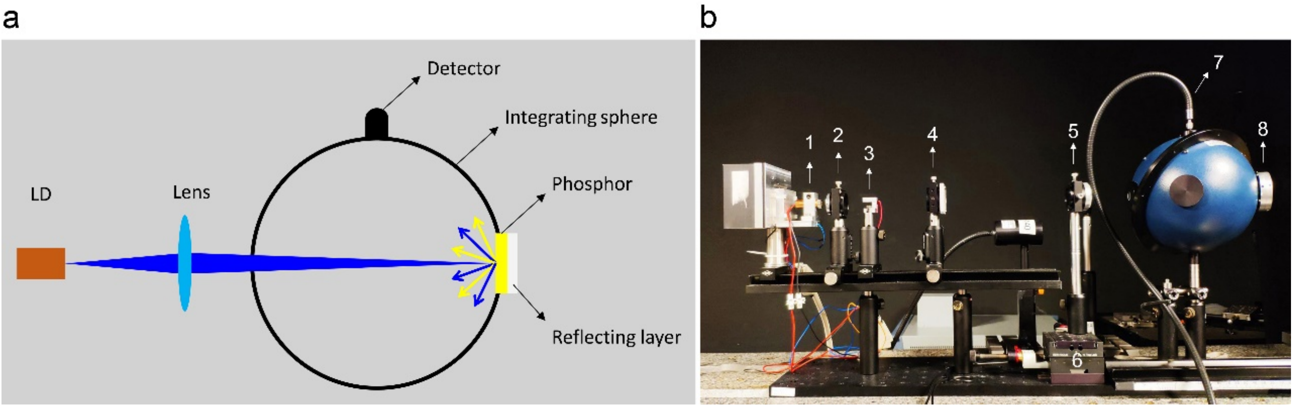


Figure 2. a) schematic and b) photo of the automated spectroradiometric characterization setup.

Furthermore, a setup for characterizing the luminescent spot size from the phosphor materials has been developed. Both setups have been used extensively to thoroughly characterize different phosphor materials. These characterizations have led to several publications given in 5.7.1. Example results from these characterization setups are given in Figure 3 and Figure 4.

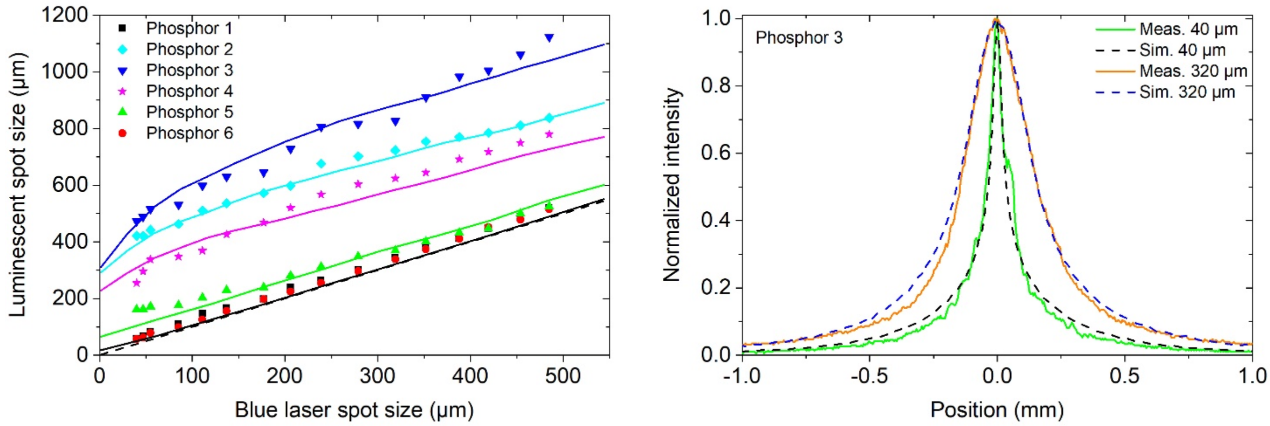


Figure 3. Measured and simulated luminescent spot sizes for different input blue laser spot sizes for 6 different phosphors (left) and measured and simulated luminescent spot cross sections for two different input laser spot sizes for phosphor number 3 (right). Ref. 3. In 5.7.1 Scientific articles.

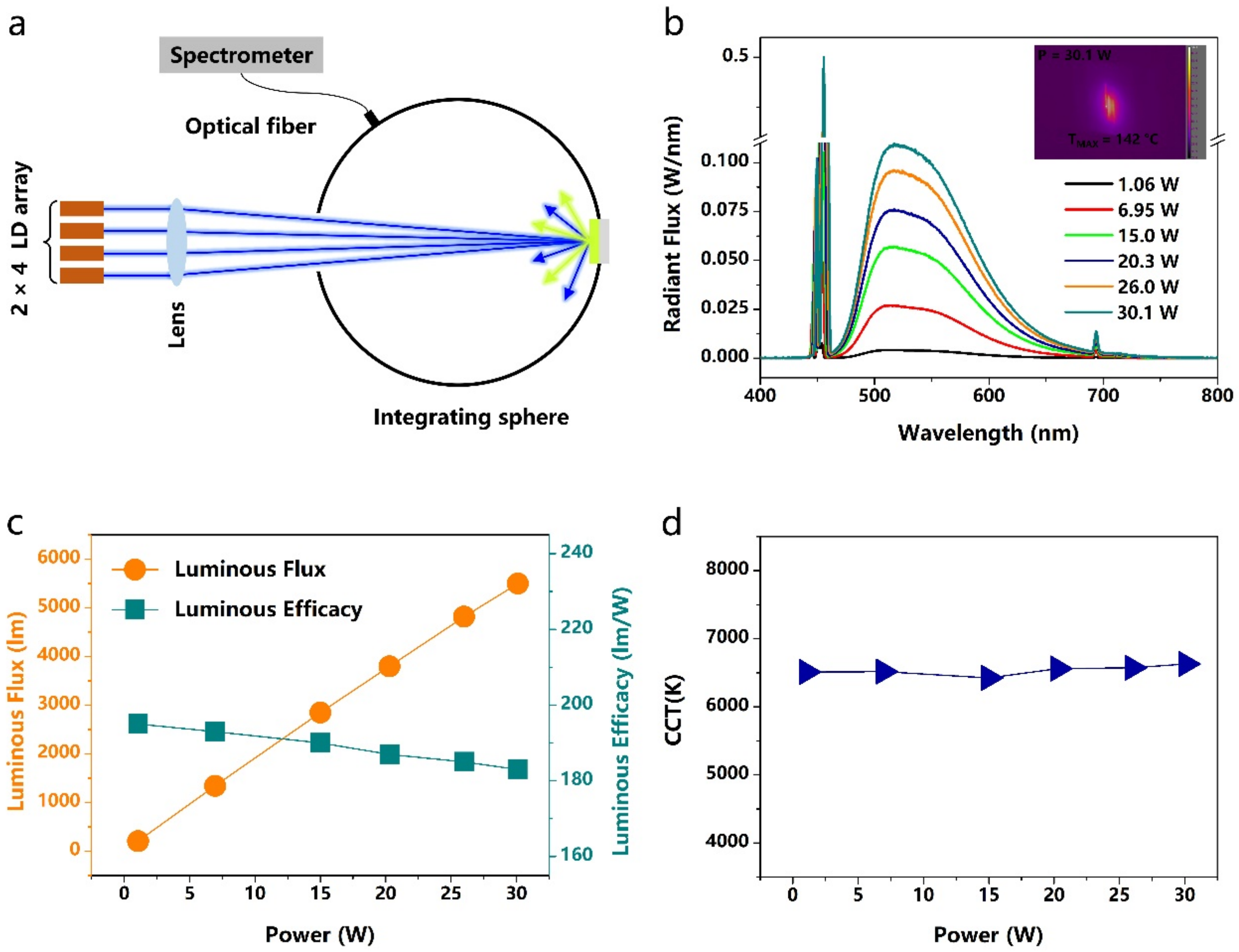


Figure 4 Setup for measuring luminous flux from a reflecting phosphor material (a), Measured spectra for a Ce:LuAG composite phosphor at different laser power levels (b), Luminous flux and efficacy vs input laser power (c) and variation in correlated color temperature (CCT) with laser power (d). Ref. 4. In 5.7.1 Scientific articles.

One of the challenges with laser lighting is the cold white light with low color rendering characterized by a CRI of 60-70. In order to improve this new red emitting phosphor materials has to be developed. In ref. 7. in 5.7.1 Scientific articles, a $CaAlSiN_3$:Eu/glass composite film is characterized for red emission, as shown in Figure 5. An efficiency of 40-60 lm/W is achieved.

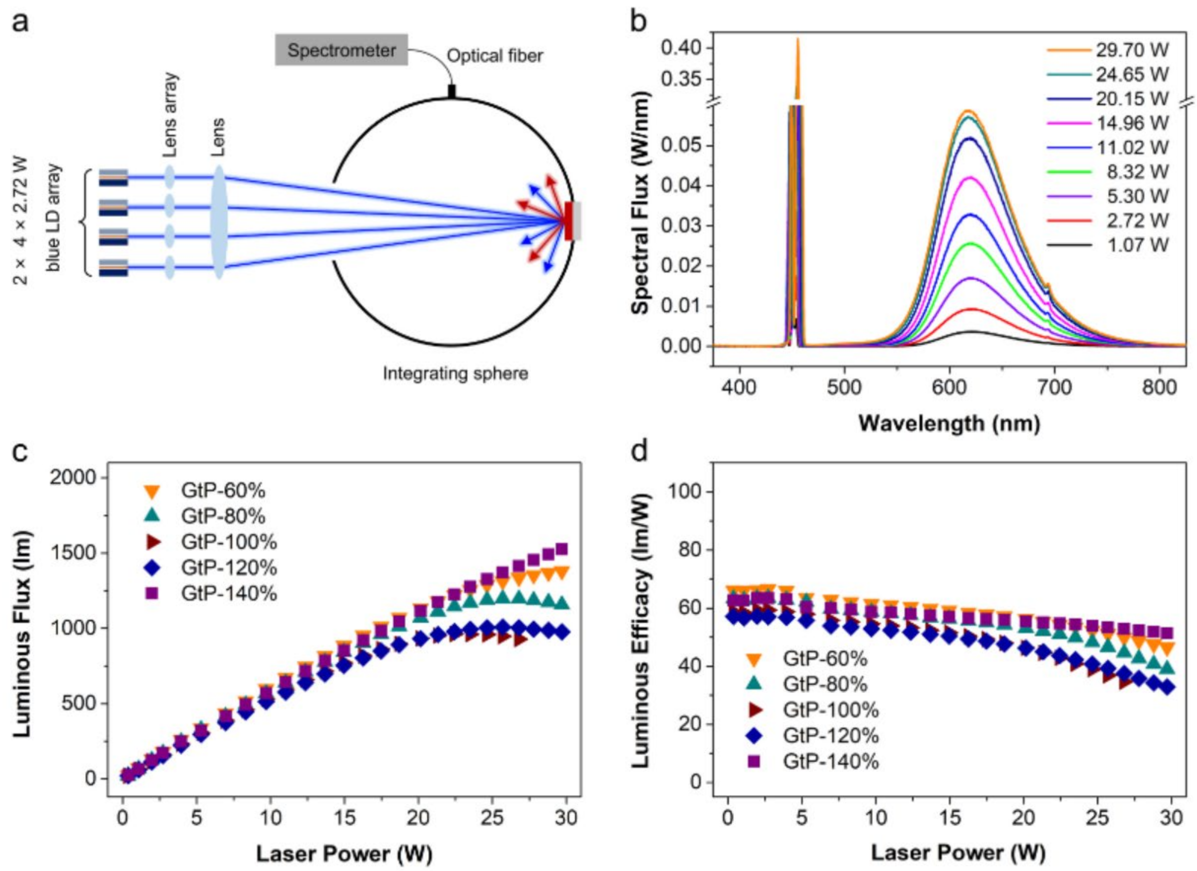


Figure 5 Spectroradiometric characterization of red emitting phosphor material, Ref. 7. in 5.7.1 Scientific articles.

The project aimed at developing and demonstrating two novel types of laser based light engines. In the following two sections the developed two types of laser based light engines are described.

5.3 Single point light source

The Single point LS is a pure laser based light engine where blue laser light is focused on to a phosphor material and where the resulting white light is a combination of the phosphor converted light and the reflected and scattered blue laser light.

Several types of Single point LS have been developed and demonstrated. Two types have been developed on the basis of SMD laser lighting devices which have become commercially available from Kyocera SLD Laser and Nichia. An SMD component of 7 x 7 mm^2 size contains two laser diodes and a phosphor material with a size of 1 mm^2. The main difference between the two lighting devices is the phosphor geometry. In the SLD SMD a reflecting geometry is used, while in the Nichia SMD a transmitting geometry is used. The two geometries have different benefits. In the reflecting geometry, the phosphor is most efficiently cooled, while the transmitting geometry has the advantage of easier access to the emitted light and better color mixing.

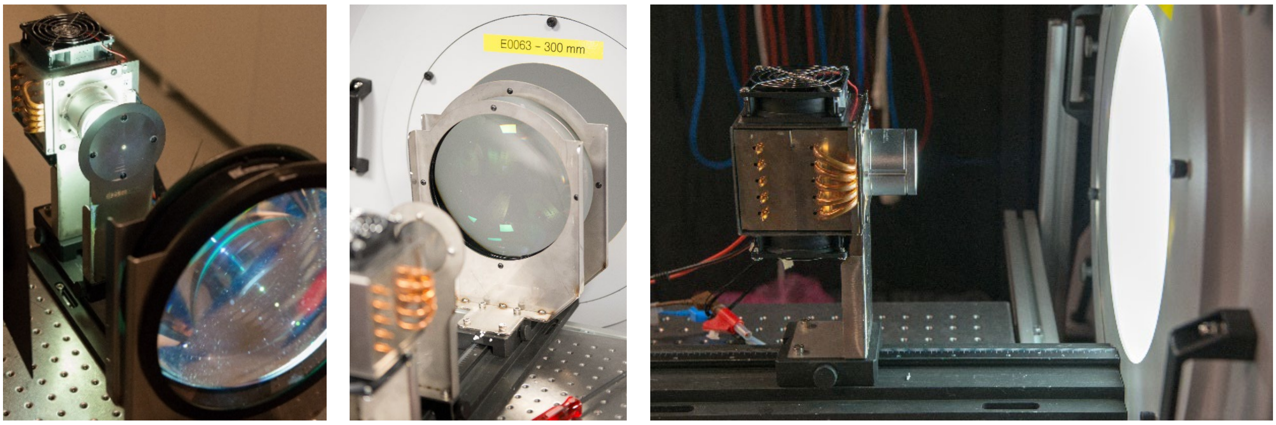


Figure 6. Single Point LS, with 7 laser light units, left: system with gate and collimation lenses, middle: system sending light through the 300 mm port of the 2m integrating sphere, right: laser light unit without gate and collimation lenses.

The single point LS has been characterized using the port of the 2m integrating sphere at DTU Fotonik. The total spectral flux has been measured before the gate and after the collimation lenses. The results are shown in Table 1.

Table 1 Measured photometric quantities for the 7 unit Single Point LS.

Setup	Luminous Flux [lm]	CCT [K]	CRI Ra	Rel. flux
Before gate	3403	5718	66.8	100 %
After col. Lenses	1452	6359	68.2	43%

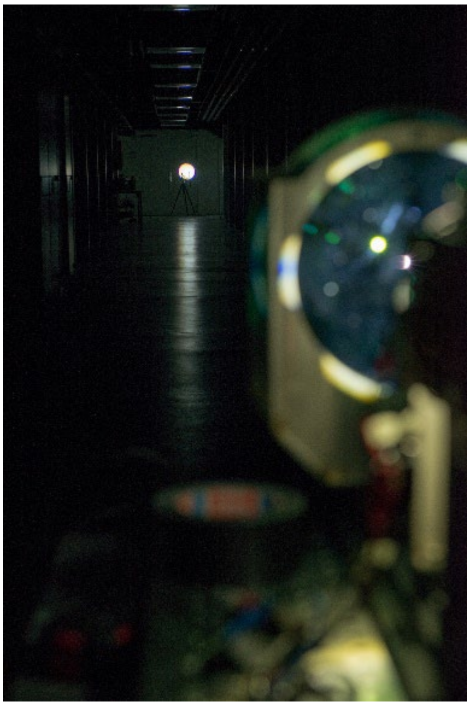


Figure 7. Photo of the Single Point LS illuminating a screen 35 m along a dark corridor.

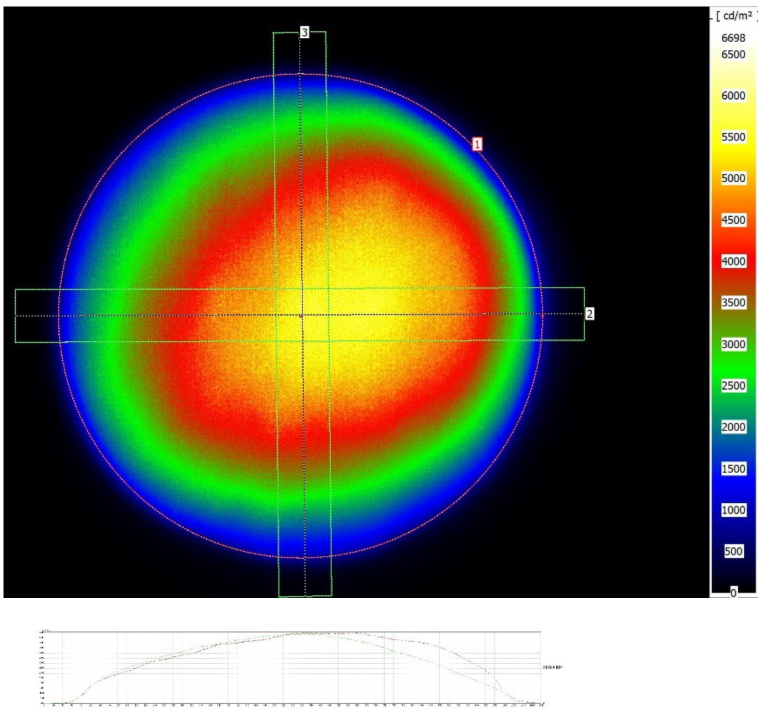


Figure 8. Measured luminance of the laser white light spot on a screen at a distance of 35 m. bottom: measured luminance along the two marked cross sections, 2 and 3.

The luminance of the Single Point LS was measured at various distances. In Figure 7 a picture of one system measured at 35 m distance is shown. The resulting luminance was characterized using a lux meter and a luminance camera. The luminance camera image is shown in Figure 8, where a relatively even luminance is achieved, however with a small off-centering caused by a slight misplacement of the gate.

A 19 emitter Single Point LS was demonstrated at an event on Risø campus, where it illuminated the water tower just outside the Campus. The distance was approximately 400 m. The Single Point LS was capable of 160 lux measured at the 400 m distance, corresponding to a measured intensity of 25 million cd even though the luminous flux was moderate at 3500 lm. Pictures of the setup and the demonstration can be seen in Figure 9 and Figure 29. A very small divergence angle of the light source enabled a small spot on the water tower despite the 400 m distance. This demonstration created significant interest for the project through social media, see 5.7.5.

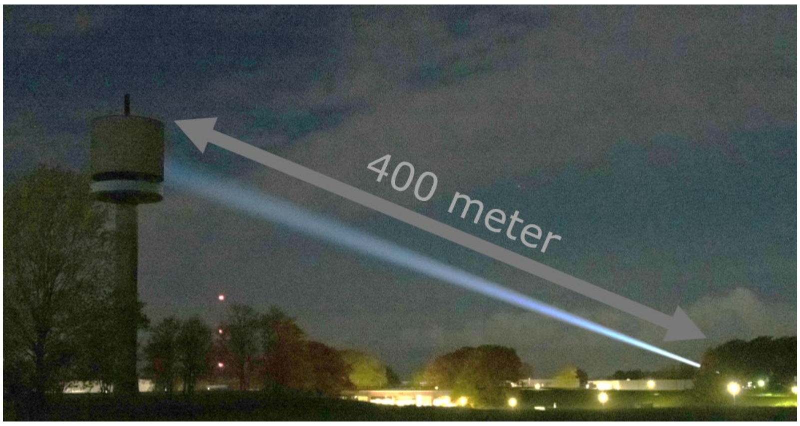


Figure 9. Photo of the 19 emitter Single Point LS (left) and of the light beam hitting the water tower at 400 m distance (right).

The above Single Point LS were all based on commercially available components from Kyocera SLD and Nichia. The dimensions of these components limits the achievable flux and luminance. Hence, in order to further improve on the performance, a high flux Single Point LS was developed.

5.3.1 High flux Single Point LS

A custom-made single point light engine based on six 75W laser diode arrays illuminating a single phosphor material was developed. The laser diode arrays are mounted on a cooling block with forced air cooling, while the phosphor is water cooled. All lasers are collimated and focused with a lens. A mirror for each laser array directs the light onto the phosphor material so that the laser light is incident at an angle. The combined laser power incident on the phosphor material is limited to 390 W by the developed power supply shown in Figure 10. The power supply can be used to either manually control each laser individually or control all lasers by DMX.

The light from each laser array is incident on the phosphor. The lens is positioned in a way to make the laser beams illuminate the majority of the phosphor surface to spread the thermal load. The phosphor material and the resulting light distribution on the phosphor through the condenser lens to capture the emitted light is shown in Figure 11. The illumination of the phosphor is relatively even with approximately 3 mm diameter.

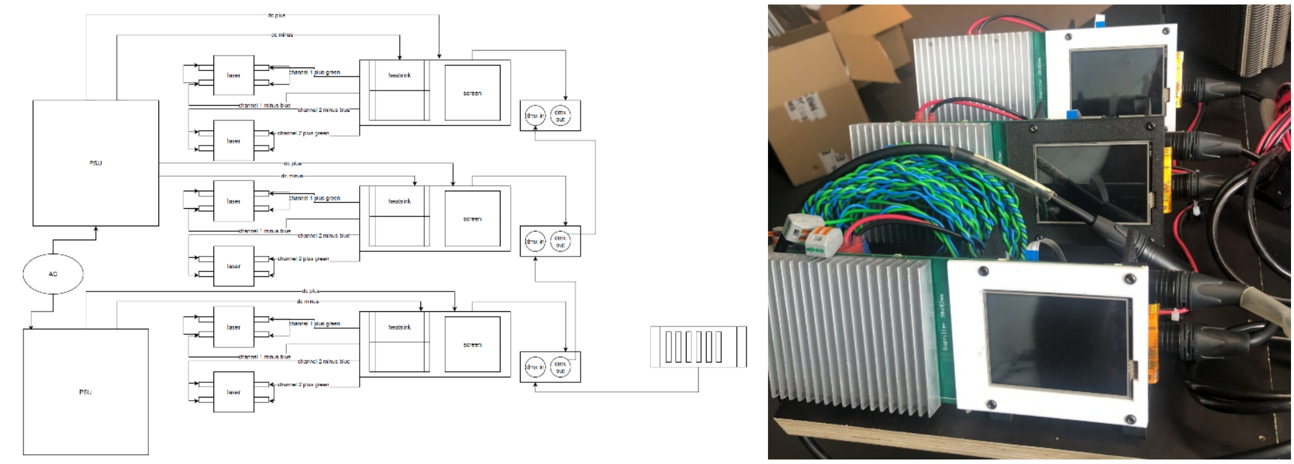


Figure 10. Left: schematic of the laser power supply system to set the current of the six laser diode arrays. Right: photo of the three driver boards with touch screen control.

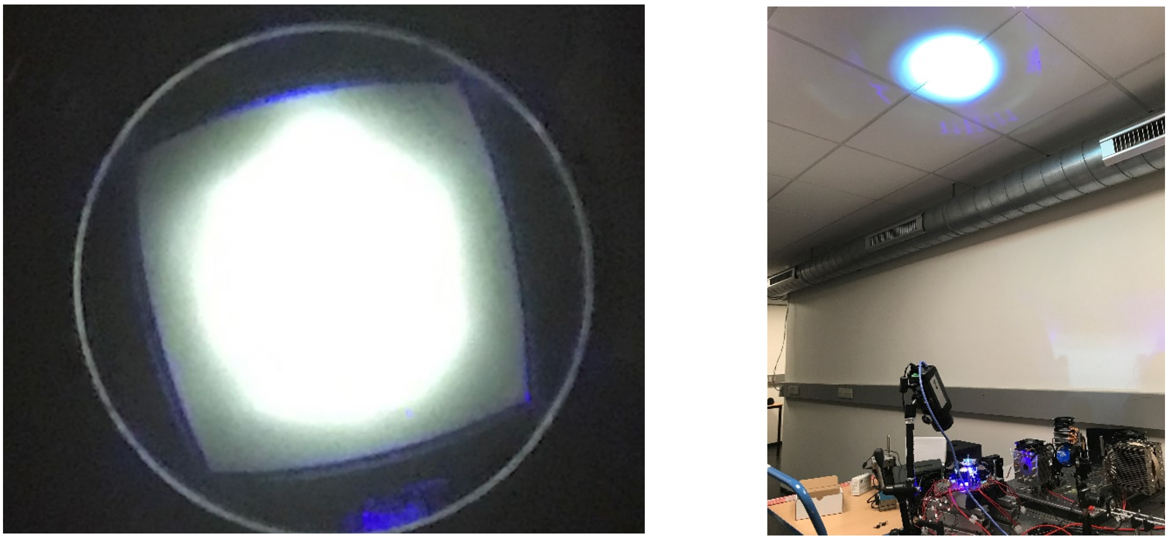


Figure 11. Picture of the light distribution seen through the condenser lens used to collect the light from the phosphor (left) and the light spot emitted by the system during alignment (right).

The output from the system was measured using a 2 m diameter integrating sphere connected to an array spectroradiometer. An example spectrum of the generated white light is shown in Figure 12. The spectrum is seen to consist of a sharp blue peak from the laser emission and a broad peak in the green-yellow-red spectral range emitted by the phosphor. In this particular spectrum, the CCT is 7712 K and the CRI is 70.5. In Figure 13 to the left the measured chromaticity of the light emitted from the single point LS in CIE 1931 chromaticity diagram is shown. In general the measured CCT values >6000K and the limited CRI is a challenge when applying such a light source in many applications. When the laser power is increased, the luminous flux increases as seen to the right in Figure 13. However, it is also seen that the luminous flux saturates at power levels above approximately 150 W. A maximum of 12084 lm was measured at 168 W input laser power. Above this laser power level the luminous flux decreases.

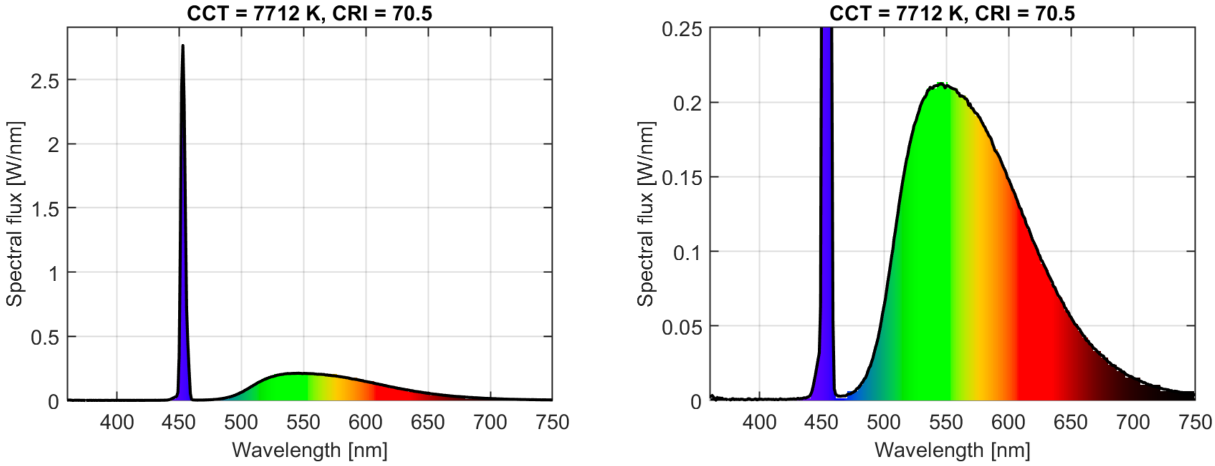


Figure 12. Measured spectral power distribution of the Single point LS at a laser level of 168 W with a total luminous flux of 12084 lm. Right: zoomed to the level of the phosphor emission.

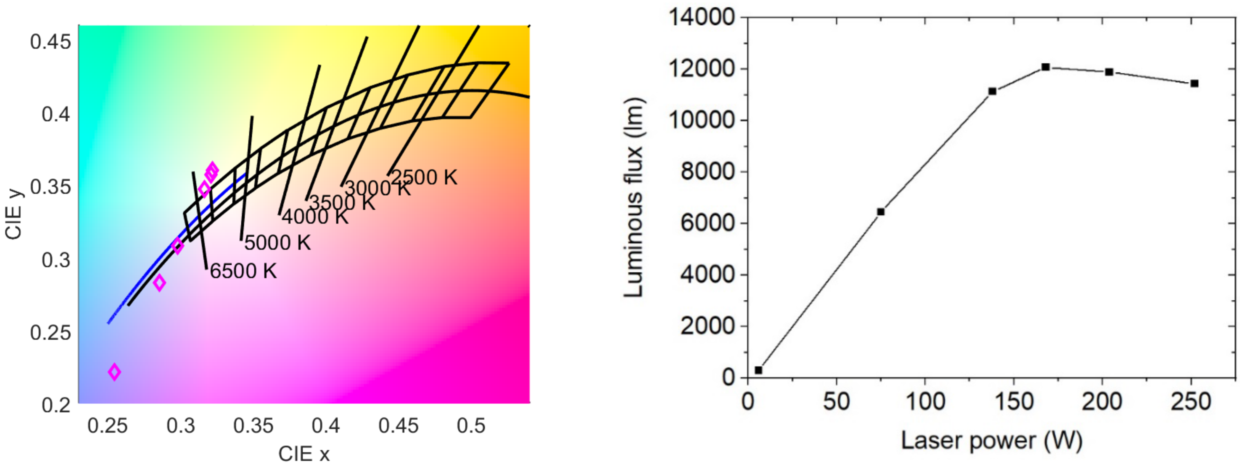


Figure 13. Measured chromaticity of single point LS with a white phosphor in CIE 1931 chromaticity diagram (left) and measured luminous flux vs. input laser power (right).

The cause of the decrease in luminous flux was investigated and found to be thermal quenching in the phosphor material. A thermal camera, which can be seen in Figure 11, was used to image the phosphor material during operation but without condenser lenses. Thermal images at three different power levels are shown in Figure 14. Two main issues can be seen from the figure. First, the temperature distribution on the phosphor surface is seen to be inhomogeneous with a clear hot spot in the left side. Secondly, the phosphor temperature is above 400°C at an input laser power of 168 W. The inhomogeneous temperature distribution is most likely caused by an inhomogeneous laser intensity distribution. The laser intensity distribution is a results of the beams from six laser arrays impinging on the phosphor. It is not trivial to ensure an even distribution from all these beams. Another explanation could be inhomogeneous thermal contact of the phosphor to the heat sink. If voids are present in the soldering, this will significantly decrease the thermal conductivity and create hot spots. The increased temperature on the phosphor material causes thermal quenching, which is a decrease in quantum efficiency of the phosphor at elevated temperatures. Therefore, the incident blue light is not converted to green-yellow light in the phosphor. This can also be seen on the chromaticity shown in Figure 13, where the color temperature is seen to increase. This is caused by an increasing ratio of blue light compared to the green-yellow spectral components.

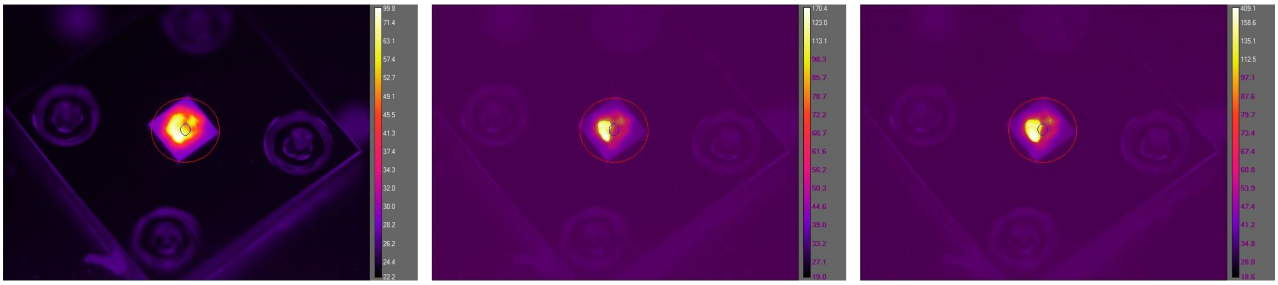


Figure 14. Thermal images of the phosphor at three different input laser power levels of 75 W (right), 138 W (middle) and 168 W (right) with temperatures reaching 100°C, 170°C and 409°C, respectively .

The development of the high flux single point LS was not concluded due to the limited project duration. However, we believe that significant improvements can be made to the system to make it a true competitor to discharge lamps. These include:

- More efficient cooling of lasers and phosphor.
- Development of optical system with more homogeneous illumination of the phosphor. This will distribute the generated heat over a larger area and limit thermal quenching.
- Development of phosphor materials capable of withstanding higher thermal load e.g., by using more thermally conductive matrix and phosphor less prone to thermal quenching.
- Development of phosphor materials with a composition better matched to generation of high color quality white light. This includes the use of a red emitting phosphor added to the green-yellow.

With the developed phosphor materials for the project and commercially available phosphors, the light quality is limited through the possible CCT and the color rendering. In order to accommodate this, a light source combining laser generated light with individual colors from LEDs was developed.

5.4 LiV8 color changeable light source

A laser light source combined with LED light for optimized color rendering and color control is called the LiV8. A demonstrator has been built in a design using dichroic filters for color mixing, where the collimated light from the phosphor material, blue high-power LED and red high-power LED is combined into an overlapping collimated beam. This is shown Figure 15 in where the output beam is directed into the measurement port of a 2m integrating sphere.

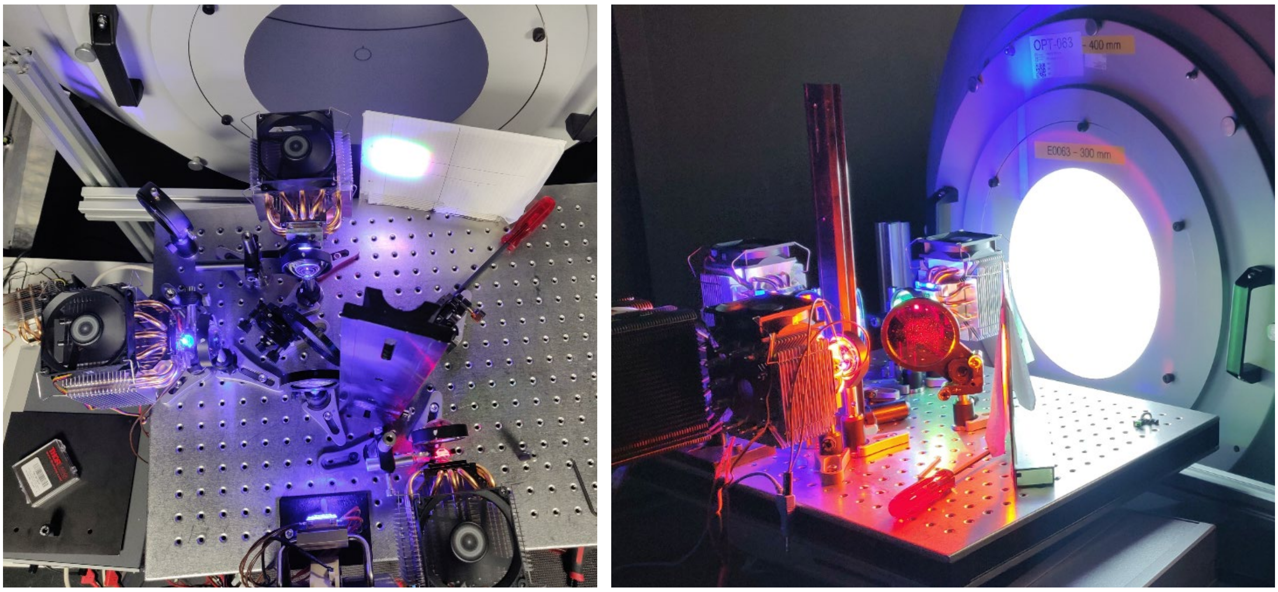


Figure 15. Photos of the LiV8 demonstrator, placed in front of the 300 mm input port of the 2m integrating sphere. Left: photo from above, blue LED is placed to the right, laser diode array in the bottom in the middle, phosphor material in the top middle, and deep red LED in the bottom to the right.

It is based on a 120 W laser diode array which excites either a green or yellow emission from a phosphor material which is combined with color mixing of blue and red light from large area high power LEDs. These are chosen from maximum flux from an emission area corresponding to the phosphor material. A 40 W blue LED at 450 nm with an circular emission area of 7 mm^2 is used. The red LED is either 48 W at 620 nm with a square emission area of 9 mm^2, or a deep red LED at 650 nm. The latter is used with the yellow phosphor. The individual parts of the LiV8 system have been characterized in the 2m integrating sphere spectroradiometer. For the emission from the yellow phosphor the emitted luminous flux has been measured as a function of the incident laser power. This is shown to the left in Figure 16, for a laser spot size of 4 mm^2 and 2.25 mm^2. The corresponding conversion efficiency is shown to the right in Figure 16.

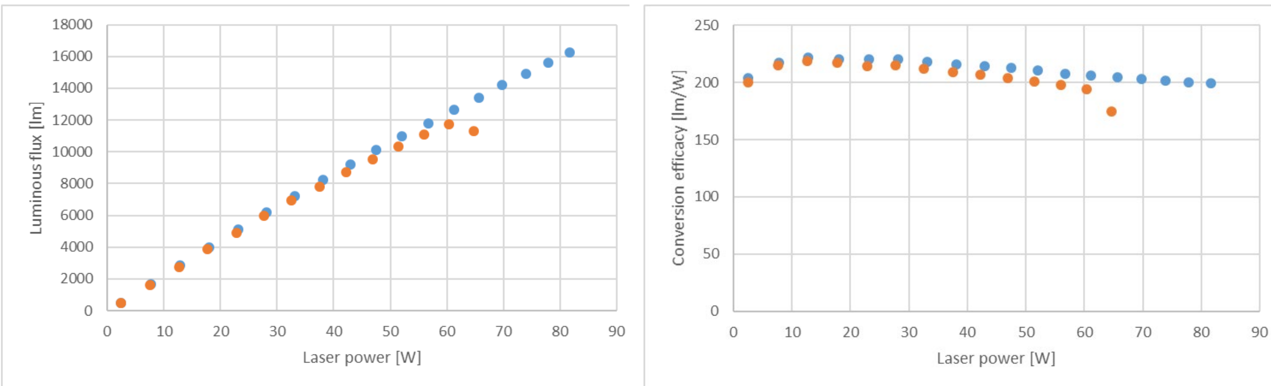


Figure 16. Measured luminous flux (left) and phosphor conversion efficacy for a ceramic phosphor used in the LiV8 color changeable light source. Blue dots correspond to a laser spot size of 4 mm^2, while orange dots are for a 2.25 mm^2 spot.

It is observed that for a 4 mm^2 laser spot size the maximum emission was more than 16000 lm, the conversion efficiency was over 200 lm/W for all laser powers. For the 2.25 mm^2 spot size, saturation occurs at approx. 12.000 lm, slightly below 200 lm/W. This corresponds to a laser power of 60 W, and 27 W/mm^2. Since we have a Lambertian emission from the phosphor material the maximum obtainable luminance can be estimated to be 1270 cd/mm^2 and 2130 cd/mm^2 for a spot size of 4 mm^2 and 2.25 mm^2, respectively.

By adding blue light to the yellow phosphor emission white light can be achieved. The measures spectral power distribution is shown in Figure 17. The CCT is 7374 K and the CRI is only 65. This is cold white light with poor color rendering.

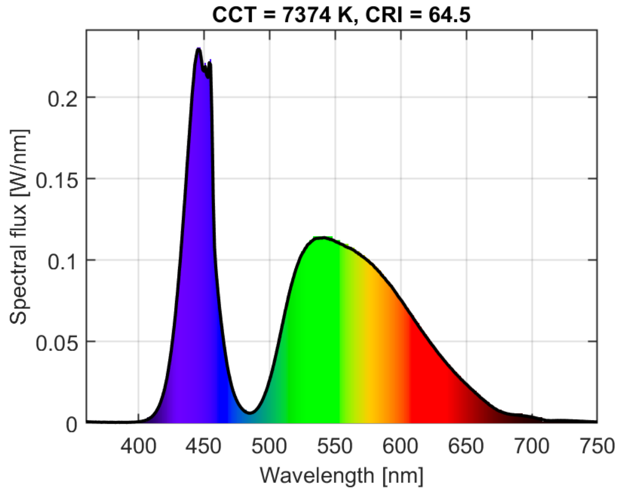


Figure 17. Measured spectral power distribution of the LiV8 using yellow phosphor and a blue LED.

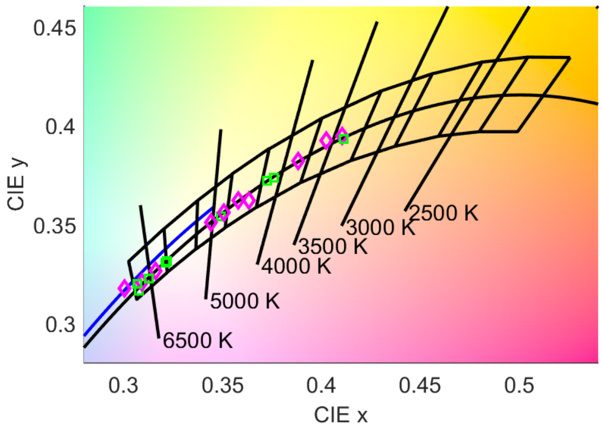
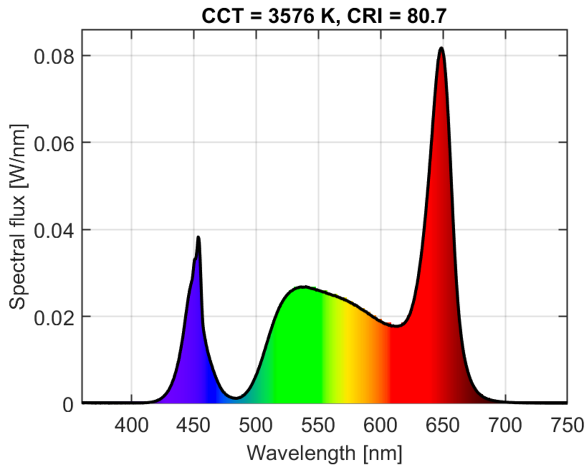
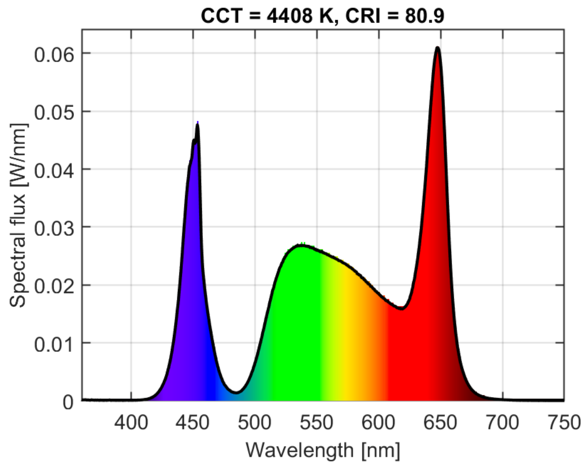


Figure 18. Measured chromaticity of LiV8 settings with yellow phosphor (magenta diamonds) and with green phosphor (green squares) in CIE 1931 chromaticity diagram

In order to achieve higher color rendering the red part of the spectrum must be added to with the red LED. To demonstrate the color quality properties of the LiV8 a number of relative settings for the laser power, blue and red LED have been measured. The chromaticities of these settings are shown in the CIE 1931 chromaticity diagram in Figure 18. It shows that these are close to the Planckian and daylight locus corresponding to light from 7400 K cold white light to 3300 K warm white light. This illustrates the possibility to control the CCT and chromaticity. The measured spectral power distributions at 4 different CCTs are shown in Figure 19.





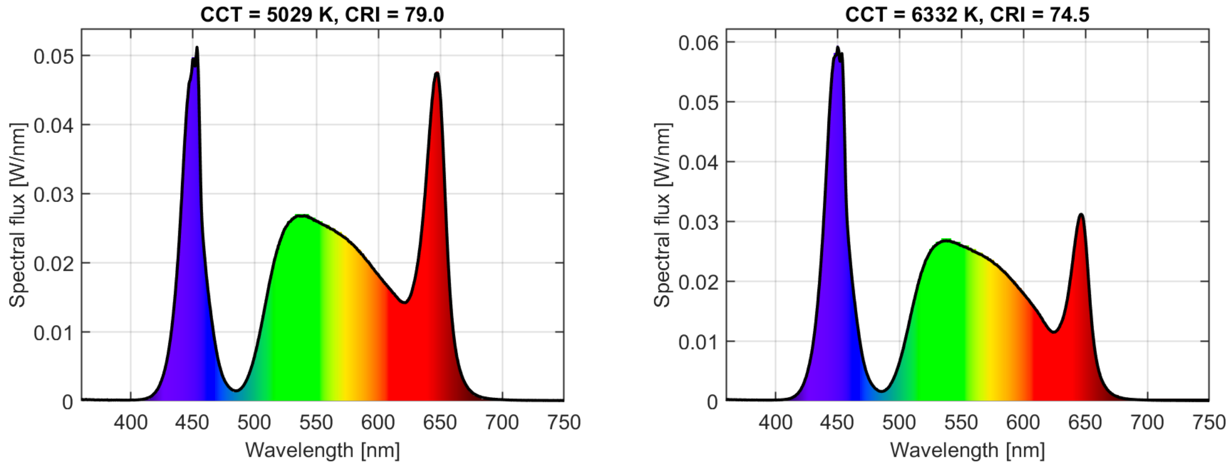


Figure 19. Measured spectral power distribution of the LiV8 using yellow phosphor and a blue and deep red LED at four different settings. The measured CCT and CRI are indicated on each figure.

These illustrate how the relative power of the blue and red LED light sets the CCT. The CRI is just around 80 for CCTs below 5000 K. This is shown in more detail in Figure 20 to the left, where the measured CRI is shown as a function of the measured CCT. For the yellow phosphor the CRI is highest for CCTs below 5000K and has a maximum of 81 around 4000 K. For the green phosphor the highest CRI is found for CCTs from 6000-7000 K and reaches 78. The obtainable luminous flux for the different settings is shown to the right in Figure 20. The luminous flux is around 2000 lm for the green phosphor and 1500 lm for the yellow phosphor. It is the maximum luminous flux of the red LED that limits the achievable luminous flux of the white light. Running the red LED at maximum current made it possible to run the laser at higher power and higher luminous flux of 2700 and 4000 lm was obtained around 4700 K The highest luminous flux of 6300 lm is for the SPD in Figure 17, with no red LED light added.

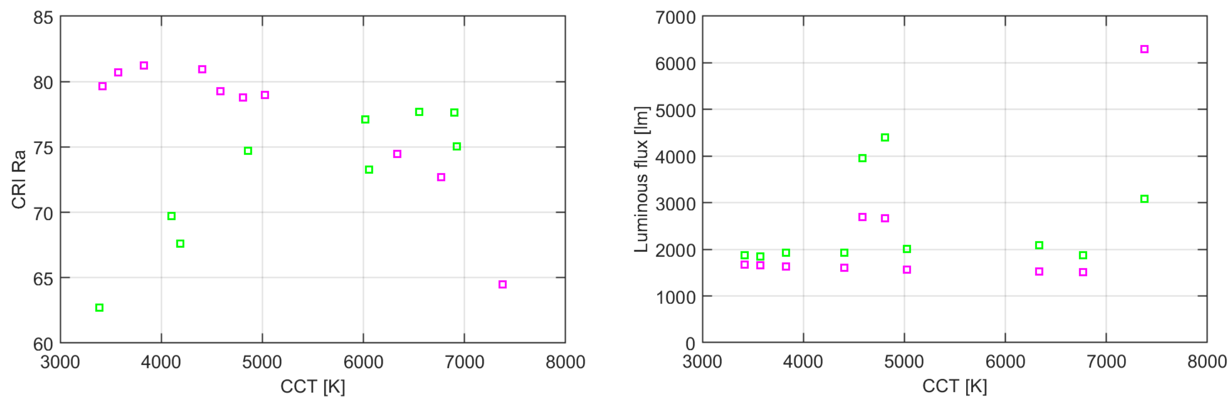


Figure 20. Measured CRI as a function of measured CCT(left) and measured luminous flux as a function of measured CCT. Data shown for yellow phosphor (magenta squares) and green phosphor (green squares).

The results of the characterization of the LiV8 light source demonstrates that it is an efficient way to excite the phosphor material and to collect the emission from the phosphor material. The light engine was capable of emitting more than 16.000 lm. The color mixing with light from a blue and red LED demonstrates that it is possible to control the CCT of the white light and to achieve a reasonable high color rendering with a CRI of around 80 for CCTs in the range from 3300-5000 K.

The chromaticity of the color mixed white light depends on a lot of parameters, individual drive currents, junction temperatures, ambient temperature and in order to be able to maintain a stable color or chromaticity of the white light over long time a color control system is needed, which is described in 5.5.

5.5 Color control and optimization

When dealing with multi-channel or multi-source lighting system, it becomes a challenge to reach the desired light output and maintain it for extended periods of time, due to the varied properties of different light generation principles (Laser, LED (various types), phosphor conversion). The various technologies for instance have different sensitivity to environmental factors such as temperature, current variations and aging. This means that color and lighting measurement control and management becomes important. Work package 5 of the project focuses on aspects of measurement, control and quality assurance. Importantly the photometric and spectroradiometric laboratory has been made ready for the measurements needed in the project see section 5.5.1.

During the project a color control and management system was developed named *Active Color Management Technology* (ACMT). This was done for control and management of multi-colored light sources such as the LiV8 tunable light engine. The ACMT uses a software control algorithm that can be used for two different purposes depending on the setup and application (see 5.5.2.1 and 5.5.2.2)

5.5.1 Quality through accurate measurement

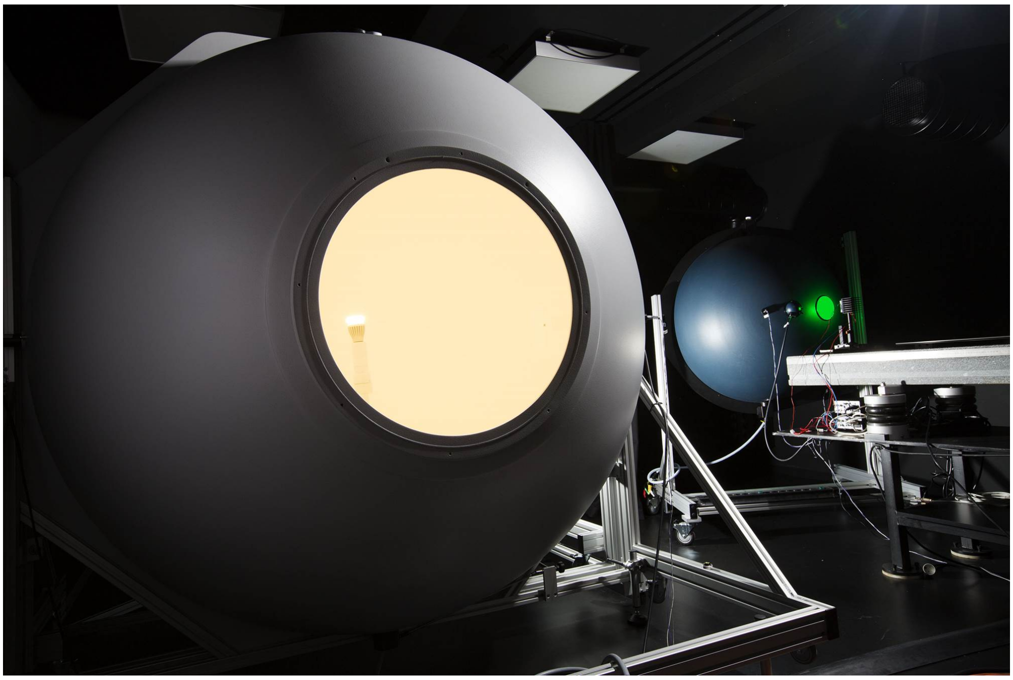


Figure 21. Integrating spheres (Ø 2m (left) and 1 m (right)) at the photometric and radiometric laboratory at DTU Fotonik were used to characterize the light output of the various demonstrators.

The photometric and radiometric laboratory at DTU Fotonik was used to support all activities throughout the project. The calibrated 2 meter integrating sphere (see Figure 15 and Figure 21) were used to achieve results such as the measurements results seen in Figure 12 - Figure 13 and Figure 17 - Figure 19. Luminance images seen in Figure 8 are done using a calibrated luminance camera.

To keep up with the latest light measurement research the project benefitted from the close affiliation between DTU Fotonik and the International Commission on Illumination (CIE). DTU Fotonik manage the Danish membership of CIE Division 2 “Measurement of light and radiation”. The project has benefited from DTU Fotonik participating in the following technical committees:

- CIE TC 2-62 Imaging-Photometer-Based Near-Field Goniophotometry
- CIE TC 2-78 The Goniophotometry of Lamps and Luminaires

- CIE TC 2-79 Integrating sphere photometry and spectroradiometry
- CIE TC 2-80 Spectroradiometric measurement of light sources
- CIE TC 2-86 Glare Measurement by Imaging Luminance Measurement Device (ILMD)
- CIE TC 2-86 2-89 Measurement of Temporal Light Modulation of Light Sources and Lighting Systems
- CIE TC 2-93 Revision of ISO 23539:2005(E) / CIE S 010/E:2004 Photometry - The CIE system of physical photometry

Valuable insights are exchanged between experts and specialist of the various fields in these committees.

5.5.2 Active Color Management Technology (ACMT)

5.5.2.1 Analysis of the color space

Based on an extensive set of data of the spectral power distribution from characterization measurements of the light source in virtually all settings of each color channel the project build up a dataset that can can be understood of as a virtual version or digital twin of the light source. Project work has gone into a version for of the ACMT algorithm which is able to automatically navigate throughout the full output space of the data set (see Figure 22).

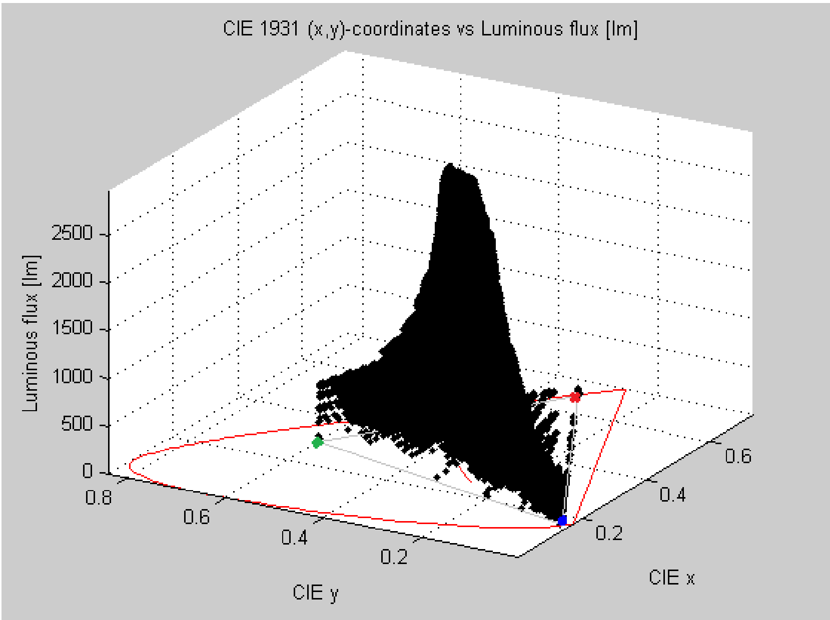


Figure 22. An approximation of the full CIE (x, y, Y) output space of the ACMT RGBWW test light source. The points of red, green and blue are indicated with colors as well as the resulting gamut in light grey color in the base plane.

Specifying, in the algorithm, a number of success criteria with respect to quality of the resulting desired light – such as color rendering (spectral power distribution), proximity to (and possibly side of) the Planckian locus (Duv and sign of Duv in science, called ±Green in the industry), correlated color temperature, intensity, etc. - the algorithm can search for and optimize color settings that will result in the lamp producing high quality light output. Such a set of known and desired settings can be used in a look-up table stored in the lamps built-in microprocessor to assist the user of the commercial product to quickly achieve the desired quality of light. ACMT in this form is currently used in BB&S's Area 48 Color lamp.

5.5.2.2 Sensor based control

A tristimulus XYZ color sensor, seen in Figure 23, with a spectral response close to that of the CIE color matching functions is mounted in a suitable place in the light fixture and the built-in processor is able to constantly measure the actual light/color output. The embedded ACMT algorithm for this application compares the measurement results to the desired output specified by the user, calculates the error and the amount of correction needed for each color. The microprocessor will apply this correction to the color output channels to keep the light with respect to both color and intensity. This happens at a rate that makes correction changes undetectable to spectators/audiences.

Under laboratory conditions this version of the ACMT algorithm has been shown to perform with very good results on a test light source using a color specification close to that of the Area 48 Color lamp (RGBWW). During test runs the light source was submitted to realistic temperature changes of close to 30ºC (otherwise resulting in visible changes in the color), and was able to keep the lights color point within a fraction of a 1-step MacAdam ellipse. Much less than what is detectable to a human eye.

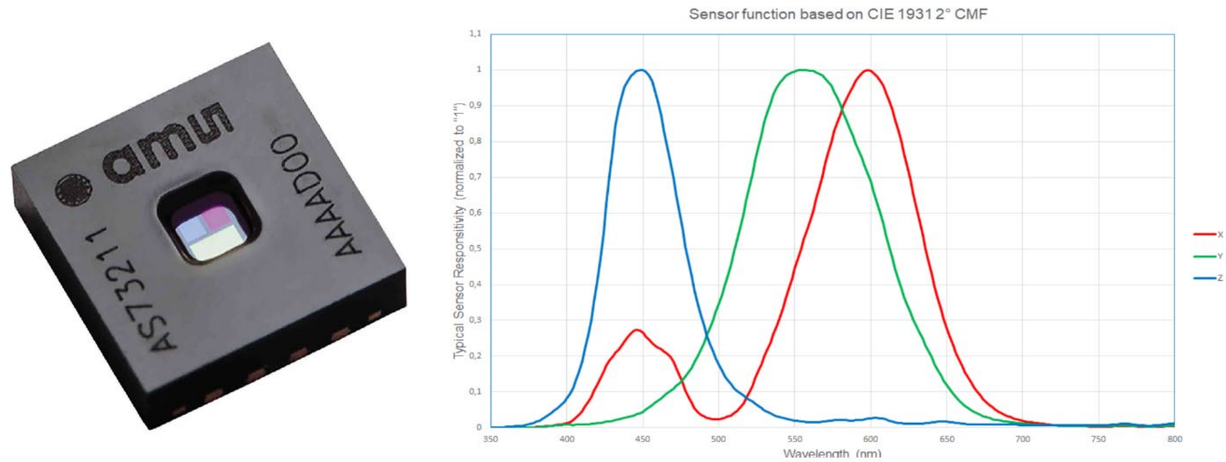


Figure 23. The ams AS73211 True Color sensor (left) and its response functions (graph to the right)

In order to make several of a kind of lamp (e.g. LiV8) produce the same light and color using the same control settings a system for calibrating a group or production batch of lamps is necessary. Such a system includes characterizing and linearizing each color channel on each lamp with respect to intensity. By finding the actual numerical relation between the channels input and output and by comparing this to the same relations on a specified reference lamp correction factors for each lamp individual channels can be calculated and stored in the production lamp own memory together with the look-up table etc. Together with an embedded color sensor and the embedded ACMT algorithm changes in each lamp light and color due to wear, change of temperature, etc. can be corrected for to make all lamps keep the desired light and color. A test of the functionality of this is shown in Figure 24, where very tight color and intensity is maintained over large temperature variation.

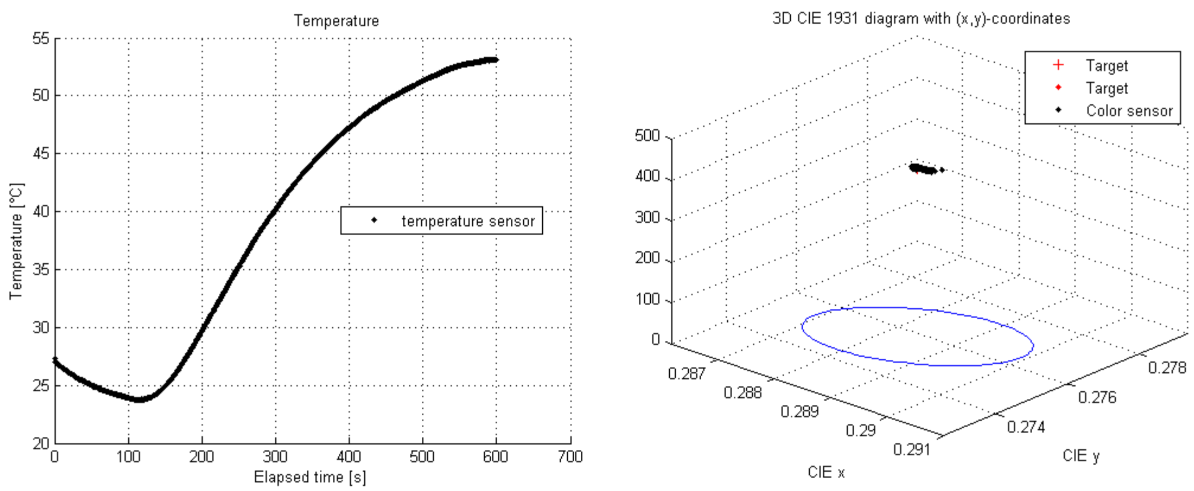


Figure 24. Graph on the left show change of temperature over progress of time. On the plot to the right the target point is indicated in red and almost totally obscured by black points (measurements from color sensor). The blue curve indicates a 1-step MacAdam ellipse around the desired target value. The height above the MacAdam ellipse (zero plane) indicates intensity value.

5.6 Commercial results

An important commercial result is the successful establishment of contacts to Nichia and Kyocera SLD Laser (https://www.kyocera-sldlaser.com/), that are essential for a commercial implementation of the laser light technology. Both companies have acknowledged the application of laser diode arrays for stage and studio lighting. These contacts have made it possible to purchase and acquire laser diode arrays that are in preproduction stage and allows the project to be on the forefront of this technological breakthrough. This is a result of the established EUDP project work carried out by the project group and the published scientific results. In the first year of the project, it was only possible to acquire blue laser components through e.g. eBay.

Peter Plesner, BB&S, are in discussion about possible volume sales and need for samples with the producers of laser diodes. This has now resulted in a contact to the Product Manager on Laser Diodes at Nichia Europe B.V. An NDA has been signed and will pave the ground for information exchange on new products and the purchase of samples for the research work.

Laser based light sources as SMD components have become commercially available during the last two years. It is Nichia and Kyocera SLD Laser that have launched laser based components that can replace LED components with a higher luminance, but with limited luminous flux. Through the project it has been possible to obtain preproduction samples of these for test in the laboratory and they have been used for producing three single point LS light engines. These SMD do not solve the problem of replacement of high-power HID lamps, which requires much higher total luminous flux from a single small emission point. Further, the light quality is limited to high correlated color temperatures and low color rendering. However, the SMD components are easy to operate and can be a good starting point in applications requiring less than 1000 lm flux as simple optics can generate higher luminance than possible using LEDs.

Despite the challenges still remaining with the SMD components, an opening to the niche market on calibration sources for high dynamic range cameras has appeared. This resulted in selling of a light source for research purposes to EPFL in Switzerland, see section 6.4.

A direct commercial result is the implementation of the new ACMT system for color control which is an integral part of BB&S's white and color tunable luminaires and light engines. The target group is BB&S' normal customers and the most important segment is studio lighting, where a homogeneous color appearance in a studio is of vital importance.

The Single point LS and LiV8 are not ready for production and more development is needed to reach the goal of making replacement light sources for HID lamps. The market for these will also be BB&S normal customers and be sold as a replacement light source for used and valuable spot lamps. This is the same scenario as when BB&S developed and commercialized LED replacement light sources for replacement of high power halogens in studio and stage lighting.

5.7 Dissemination of results

The project results have been disseminated through seminars, conferences, publications in scientific journals and social media platforms.

5.7.1 Scientific articles

1. A. Krasnoshchoka, A. Thorseth, C. Dam-Hansen, D. Dan Corell, P. M. Petersen and O. B. Jensen, "Investigation of saturation effects in ceramic phosphors for laser lighting", Materials, 10, 1407, 2017.
2. J. Xu, A. Thorseth, C. Xu, A. Krasnoshchoka, M. Rosendal, C. Dam-Hansen, B. Du, Y. Gong, O. B. Jensen, "Investigation of laser-induced luminescence saturation in a single-crystal YAG:Ce phosphor: Towards unique architecture, high saturation threshold, and high-brightness laser-driven white lighting", J. Lumin., 212, 279-285, 2019.
3. A. Krasnoshchoka, A. K. Hansen, A. Thorseth, D. Marti, P. M. Petersen, J. Xu, and O. B. Jensen, "Phosphor material dependent spot size limitations in laser lighting", Opt. Express, 28, 5758-5767, 2020.
4. J. Xu, Y. Yang, Z. Guo, A. A. S. Lancia, B. Du, B. Hu, B. Liu, H. Ji, C. Dam-Hansen, and O. B. Jensen, "Industry-friendly Synthesis and High Saturation Threshold of a LuAG:Ce/Glass Composite Film Realizing High-brightness Laser Lighting", J. Eur. Ceram. Soc., 40, 6031-6036, 2020.
5. J. Xu, Y. Yang, Z. Guo, D. D. Corell, B. Du, B. Liu, H. Ji, C. Dam-Hansen, and O. B Jensen, "Comparative Study of Al_2O_3-YAG:Ce Composite Ceramic and Single Crystal YAG:Ce Phosphors for High-Power Laser Lighting", Ceramics International, 46, 17923-17928. 2020.
6. J. Xu, Y. Yang, Z. Guo, B. Hu, J. Wang, B. Du, B. Liu, H. Ji, C. Dam-Hansen, O. B Jensen, "Design of a CaAlSiN3:Eu/Glass Composite Film: Facile Synthesis, High Saturation-Threshold and Application in High-power Laser Lighting", J. Eur. Ceram. Soc., 40, 4704-4708, 2020.
7. J. Xu, Y. Yang, Z. Jiang, B. Hu, X. Wang, H. Ji, J. Wang, Z. Guo, B. Du, C. Dam-Hansen, O. B. Jensen, "$CaAlSiN_3$: Eu/glass composite film in reflective configuration: a thermally robust and efficient red-emitting color converter with high saturation threshold for high-power high color rendering laser lighting", Ceram. Int. 47, 15307-15312, 2021.

5.7.2 Scientific presentations

1. C. Dam-Hansen, "SpotLase – introduction to the project goals and milestones going back to the V8 project", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.
2. O. B. Jensen, "Laser-based street lamps – opportunities and challenges", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.
3. A. Krasnoshchoka, "Saturation effects in ceramic phosphors", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.
4. P. Plesner, "BBS and the future of stage lighting", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.
5. J. Lindén, "Laser-Induced Phosphor Thermometry – another way to use phosphors", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.
6. X. Jian, "Minimizing saturation effects in highly irradiated phosphors materials", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.
7. A. Thorseth, "Precise measurement of high dynamic range spectra resolving both laser lines and phosphor peaks", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.
8. A. Czesnakowska, "Laser lighting research at Université Toulouse", 20-3-2018. Seminar on phosphor converted laser lighting, DTU Fotonik, Risø.

Figure 25. Photos from seminar on phosphor converted laser lighting, 20-3-2018, at DTU Fotonik, Risø.

9. A. Krasnoshchoka, J. Xu, A. Thorseth, C. Dam-Hansen, and O. B. Jensen, “High luminous flux laser lighting using Single-Crystal Ce:YAG Phosphor”, Presented at 2019 IEEE High Power Diode Lasers & Systems Conference, 2019, Coventry, England.
10. J. Xu, Y. Yang, B. Du, C. Dam-Hansen, O. B. Jensen, ”Design of a LuAG:Ce/Glass Composite Film Realizing High-luminance Laser Lighting”, Phosphor Safari 2019: International Symposium on Luminescent Materials, Xiamen, China, 16 Nov 2019.
11. O. B. Jensen, “High luminance laser lighting”, Invited talk at the annual meeting of the Danish Optical Society, 14-15 November, Lyngby, Denmark, 2019.
12. O. B. Jensen, A. Krasnoshchoka, A. K. Hansen, A. Thorseth, D. Marti, J. Xu, and P. M. Petersen, “Limitations to emission spot size in laser lighting” Proc. SPIE 11302, Light emitting devices, materials, and applications XXIV, 11302-10 (3 February 2020).

5.7.3 Articles for Danish industry

1. O. B. Jensen, “Lasere som en del af fremtidens belysning?”, Trafik og Veje, Oktober, 32-34 2018.
2. A. Thorseth, C. Dam-Hansen, O. B. Jensen, “Vil fremtidens belysning komme fra lasere?”, Lys, 3, 32-33, 2019. See attached document: *Vil fremtidens belysning komme fra lasere.pdf* *https://center-forlys.dk/artikel/vil-fremtidens-belysning-komme-fra-lasere/*
3. L. Hovgaard, Blå laser sniger sig ind på LED, Ingeniøren (News of IDA: The Danish Society of Engineers), May 2021 https://ing.dk/artikel/bla-laser-sniger-sig-ind-pa-led-246923

5.7.4 Presentations for Danish industry

Results include successfully arranged and completed seminars and talks at one day seminars:

1. Carsten Dam-Hansen og Anders Thorseth, ” Laserbelysning til erstatning for udladningslyskilder med høj intensitet”, seminar ”LED THERE BE LIGHT”, Den Danske Scenekunstskole, 13-12-2018.

   Arranged by DDSKS, https://ddsks.dk/en/further-education, with moderator Jesper Kongshaug, 35 participants:

Figure 26. Photo collage from "LED THERE BE LIGHT" seminar, posted on LinkedIn.

2. Brad Dickson, “LED Lighting and its Relationship to the Camera”, seminar at Risø, DTU Fotonik, 11-6-2019, and at BB&S, 12-6-2019.

   Seminar with Brad Dickson, former head of lighting at Canadian Broadcasting Corporation, CBC, held both at DTU Fotonik, Risø campus and at BB&S, on the 11th and 12th of June 2019.

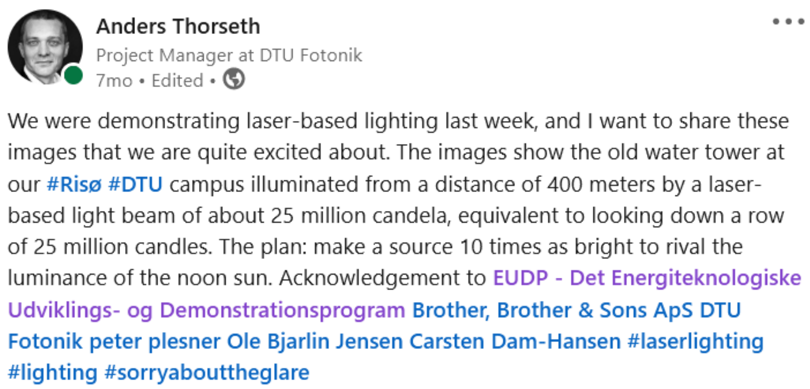
Figure 27. Photo collage from seminar, posted on LinkedIn.

3. Dam-Hansen, C. Munch K., “Status for LED og nye lyskilder”, invited talk at Lysets dag 2020: ”Lys og de 17 verdensmål”, 22-10-2020. https://orbit.dtu.dk/files/238422635/Pr_sentation_Lysets-dag_2020.pdf , video https://youtu.be/rClmC0gUYgA

4. Plesner P., ”Lighting people and buildings”, Online virtual visit arranged for Den Danske Scenekunstskole, 12-1-2021 https://ddsks.dk/da.
5. Dam-Hansen C. and Thorseth A., ”Laserbelysning til erstatning for udladningslyskilder med høj intensitet”, Online virtuel visit arranged for Den Danske Scenekunstskole, 12-1-2021 https://ddsks.dk/da.

5.7.5 Social media

During the project social media was used to promote the aspects of the project that was expected to be of interest to the community. The most successful of these postings is shown in Figure 28 and Figure 29:


Anders Thorseth
Project Manager at DTU Fotonik
7mo • Edited •

We were demonstrating laser-based lighting last week, and I want to share these images that we are quite excited about. The images show the old water tower at our #Risø #DTU campus illuminated from a distance of 400 meters by a laser-based light beam of about 25 million candela, equivalent to looking down a row of 25 million candles. The plan: make a source 10 times as bright to rival the luminance of the noon sun. Acknowledgement to EUDP - Det Energiteknologiske Udviklings- og Demonstrationsprogram Brother, Brother & Sons ApS DTU Fotonik peter plesner Ole Bjarlin Jensen Carsten Dam-Hansen #laserlighting #lighting #sorryabouttheglare

Figure 28. LinkedIn post describing the 25 million cd result which gained over 4400 views when posted

Figure 29. Image used to illustrate the demonstration of the 25 million candela light source.

Demonstration of 25 million candela laser based light source posted on LinkedIn https://www.linkedin.com/posts/andersthorseth_risaeo-dtu-laserlighting-activity-6730019128360345600-SETh (Viewed by 4.400 LinkedIn users)

6. Utilisation of project results

6.1 Utilization of technological results

The technological results of the project will mainly be utilized by BB&S in their product line for lighting of stage and TV/movie studio production. The laser-based concepts developed in the project are expected be developed into new products during the coming years. For this development BB&S will be using the critically important supplier network for the cutting-edge components (see section 5.6), the basic research described for instance in section 5.2 and the novel approaches developed in the project towards light engine development (sections 5.3 and 5.4). The project has given important insights into the availability and pricing of the important key components of this technology, that is needed for commercialization (see section 6.2).

The *ACMT* system developed in the project (section 5.5.2) will be used directly in BB&S products as it is not dependent on the pricing and development of laser diode manufacturers, or development of resilient and efficient phosphors.

DTU Fotonik will utilize the general knowledge increase and public results to engage with Danish and international industry and academia for further research and development of this technology for fitting applications, such as calibration sources (see section 6.4) and search and rescue spot lamps, and other applications where this technology will yield superior results.

6.2 Commercialization

The following will describe the utilization of the commercial results in the project, as well future turnover, exports, employment and additional private investments.

The establishment of contacts to Nichia and Kyocera SLD Laser will be utilized by BB&S for a commercial implementation of the laser-based lighting technology. It is essential that both of these companies have acknowledged the application of laser diode arrays for stage and studio lighting. The possibility to purchase and acquire laser diode arrays both from line production and in preproduction stage, will allows BB&S to continue being on the forefront of this technological frontier. Concretely, BB&S, are in discussions about possible volume sales and need for samples with the producers of laser diodes. The basis of this is the contact to the Product Manager on Laser Diodes at Nichia Europe B.V. The signed NDA will pave the way for information exchange on new products and the purchase of samples for development work.

BB&S will utilize the integrated laser-based light source SMD components that have become available to the partners during the project. The laser-based components from Nichia and Kyocera SLD Laser are aimed at replacing existing LED components based on their higher luminance. The project has given possibilities to obtain preproduction samples of these. This will enable development and tests in the laboratory and these samples have already been used for producing three *single point LS* light engines. These SMDs do not solve the problem of replacement of high-power HID lamps, which requires much higher total luminous flux from a single small emission point. However, the available SMD components are easy to operate and will work as a good starting point for BB&S in applications requiring less than 1000 lm flux. Here simple optics can generate higher luminous intensity than what is possible using LEDs.

The implementation of the new ACMT system for color control can now be an integral part of BB&S's white and color tunable luminaires and light engines. The target group will be BB&S' regular customer profile with special focus on the segment of studio lighting, where homogeneous and stable color appearance is of vital importance. The impact of implementation of the ACMT has led to employment 1 full time employee at BB&S, which will be expanded to two in the future in order to implement the technology fully.

The results regarding the development of the Single point LS and LiV8 will be utilized by BB&S as a solid foundation to further the development needed to reach the goal of making replacement light sources for HID lamps for stage and studio lighting. The market for these will be BB&S normal customers and be sold as replacement light sources for used spot lamps as well as high profile spot lamps. This is the same scenario as when BB&S developed and commercialized LED replacement light sources for replacement of high-power halogens in studio and stage lighting.

The COVID-19 situation has hit the market for event lighting and large budget movie production especially hard. Therefore BB&S have not yet seen the effect in increased turnover. Private investments is part of BB&S present strategy and it is expected to continue in the future with new investments within the next 3-5 years.

Despite the challenges still remaining with the SMD components, an opening to the niche market on calibration sources for high dynamic range cameras has appeared. This resulted in selling of a light source for research purposes to EPFL in Switzerland, see section 6.4.

6.3 Market situation

The following will describe the competitive situation as well as competing solutions and barriers of sales, and how these will be handled.

After the launch of SMD laser lighting components with total luminous flux from 500-1400 lm a number of low power and very high intensity products like flashlamps have entered the market. However, these are limited by the luminous flux of the single SMD and not a significant competitor for the entertainment lighting market. In this market segment of high-power laser-based beam lights, luminous flux has typically to exceed 10000 lm. The project partners are not aware of any competing products at this point in time and none have been commercialised during the project period.

BB&S see a clearly outlined niche market in specialty lighting that can handle a high entry price of these products at this point in time. BB&S will however continue to work with laser manufacturers to reach a lower price level and higher efficiency that will fit the more general lighting market. In order to achieve volume production of laser diode modules, yielding lower prices and higher efficiency will lead us into larger market segments.

BB&S see a clearly outlined niche market in specialty lighting that can handle a high entry price of these products at this point in time. BB&S will however continue to work with laser manufacturers to reach a lower price level and higher efficiency that will fit the more general lighting market.

With respect to ACMT we have not seen any competing products where internal sensing and measurement is used for real time color control and consistency. The internal sensing will be fully implemented in a product before the end of 2021. However, most competitors use an external calibration method of their fixtures which does not foresee the aging of light components, operating temperature, and they need to recalibrate on a yearly basis.

The limited light quality in high correlated color temperature and low color rendering sets an entry barrier, which has to be overcome. This can be done through cooperation with phosphor material manufacturers and through further research and development in phosphors materials.

6.4 Laser lighting as a calibration source

As a direct result of the project, DTU Fotonik has been commissioned by the EPFL École polytechnique fédérale de Lausanne, in Switzerland, to build a laser-based calibration source for luminance measurements. The high stability, directionally and homogeneity of the light, is attractive for calibration applications. The source was designed, assembled shipped and is now in the process of being implemented at EPFL. If this assignment goes well, DTU Fotonik could, through a spin-out, start a small production of the laser lighting calibration source. The description of the results has been submitted for consideration as a conference paper at the CIE 2021 midterm meeting, in September.

Having accurate and stable calibration available for the light measurement community will further the policies directed towards higher efficiency through reduction of wasted energy and inefficient products.

6.5 Towards a better environment

The impact from this project works towards the EUDPs strategic goals via the potential for resource savings, and is tied into the specific circumstances surrounding stage and show lighting. These specifics are:

- Usage of electrical power, highly concentrated in time and place
- Usage during peak power demand
- Current technology containing mercury
- Current technology has a very high standby consumption

The project result has moved the state art of stage lighting in Denmark to a higher level, estimated TRL 3 to TRL 6. The project has resulted in a considerable decrease in the time to market for lighting products with higher efficiency for the tasks in stage and studio lighting.

The results from the project will support the efforts in the IEA Solid state lighting annex, where Carsten Dam-Hansen is expert on LED light and light measurement.

6.5.1 Summary of the impact on energy consumption and the environment

- **Security energy of supply:** Implementing this technology reduces marginal energy use, causing less stress to the energy system
- **Independence of fossil fuel:** The reduced need for marginal energy is directly linked to reduction in use of fossil fuels for backup power
- **Climate and environmental considerations:** The reduced marginal energy consumption, benefits the CO_2 footprint, secondarily the technology displaces toxic mercury and reduces waste
- **Cost-effectiveness:** The proposed technology offers higher energy efficiency, lower maintenance costs and a complete elimination of costly standby power consumption

The following calculations are based on these estimates:

• Current number of light fixtures in Denmark:	10 000
• Average power consumption of arch fixtures:	1000 W
• Average power consumption of laser based fixtures:	100 W
• Arch lamp changes per year:	8
• Danish part of the global stage lighting market:	1%
• $C0_2$ emission from gas powered electricity generation:	500 gCO_2eq/kWh

6.5.1.1 Security of energy supply

The impact on the security of supply of electricity stems from the fact that large live TV, theatre and stage productions typically takes place in the evening, coinciding with peak electrical consumption. The power consumed at this peak of daily consumption will therefore be marginal consumption, which often requires backup capacity, such as gas power plants. This energy usage pattern is therefore often the most expensive and polluting. When project results are used to replace lamps of high power consumption with lamps of much lower consumption it is estimated that a 90% reduction is possible. Thereby a significant marginal usage of energy can be removed. This is a key consideration in modern energy systems, where renewables has to be included in the energy mix. As seen in Figure 30 the production price of marginal energy consumption can be several times the average price. Some one-off events even has to bring in highly inefficient diesel generators to fulfil the energy requirement for lighting alone.

As an example: On a Saturday evening it is not unrealistic that 10 000 arch lamps would be in simultaneous operation across Denmark. This will result in a power consumption around 10 MW, equivalent to the power produced by several large wind turbines running at maximum capacity.

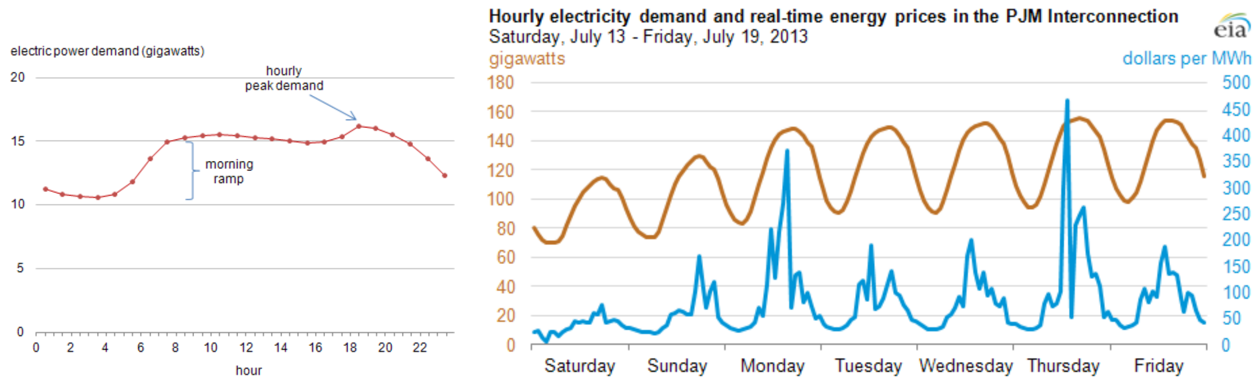


Figure 30. Demand for electrical energy throughout the day a) and the effect on the price per MWh during a week b) (Source eia.gov).

6.5.1.2 Independence of fossil fuel

When the project results are implemented as products for stage and studio lighting it will lead to a decrease in dependency on fossil fuels by reducing the need for backup capacity in the energy system to power during the peak demand period. The ability to remove marginal energy consumption will be increasingly important in the future as the energy system is populated by non-dispatchable renewable sources, such as wind and solar energy. In a typical situation the backup energy is supplied from a natural gas power plant. Replacing an arch lamp with a laser based light source will lead to a reduction of approximately 4 tons of CO_2 a year for a single replacement unit. Due to the marginal nature of the energy consumption, this demand is unlikely to be covered by renewable sources in most case.

6.5.1.3 Environmental improvement

Besides the energy savings and the savings related to lower maintenance (fewer lamp changes), there is another environmental consideration. The arch lamps that laser based lighting technology is going to replace, contains the toxic metal mercury. The arch lamps which have to be replaced at regular intervals (roughly 8 times annually) therefore contribute to the mercury disposal challenge with approximately 1 g pr. 10 kW per 1000 hours of use. Due to the significantly longer lifetime a single laser light engine with no toxic mercury content will enable substitution of at least 30-50 arch lamps. A large laser driven light source with 1000 W equivalent output and 50000 hours of operation will displace approximately 10 grams of mercury during its lifetime. For comparison this is approximately 50000 times the Danish threshold value for daily intake of mercury, for each day during a 50000 hour period.

6.5.1.4 Cost-effectiveness

The potential cost-effectiveness of the laser lighting for stage and studio lighting have several aspects:

- Arch lamps needs to be changed often to ensure stabile output, laser based replacements do not.
- The very high standby consumption of arch lamps will be completely eliminated by laser based devices.
- The excess heat and power consumption of arch lamps cause secondary effects such as larger heat load for ventilation and heaver equipment for transport, which will be greatly reduced

For lighting systems based on arch lamps, the lamp has to be changed approximately every 750 hours or usually even more often to ensure stable light output and homogeneous color of a whole setup of lamps. The replacement lamps are about 0.13 € per lumen output so the total expense can be quite large: 130 k€ for 50000 hours of operation of a 25000 lm luminaire.

An important consideration is that while in use on stage the arch lamps cannot be turned off. While in standby mode they can only be dimmed to around 50%, and have to be mechanically blocked to turn off the light output. This means that during a stage or studio production even when no illumination is needed the lamps are still consuming large amounts of power. Table 2 shows a typical application of this type of spot light in a show setting and compares the energy consumption of arch and laser based fixtures. It is evident that the standby consumption of the HID lamps play a heavy part in the energy consumption for lighting of a typical show, and large savings, on the order of 95% can be obtained by switching technology. This waste of energy and lamp lifetime will be completely removed with laser driven light sources. In an indoor environment, the excess heat also has to be removed using ventilation systems, this extra expense can be reduced by the result of this project.

Due to the large power requirements of the arch light sources, large and heavy power supplies also have to be transported together with the lighting equipment. Reduction in the power consumption means less transport in relation to one-off events and tours.

Table 2 – Example of the energy usage for lighting a typical show, comparing HID and laser based lighting.

	Duration		Power per fixture		Single unit energy use		Total energy use	
	Total	Actual use	HID	Laser	HID	Laser	HID	Laser
	[hours]		[W]	[W]	[kWh]	[kWh]	[MWh]	[MWh]
Setup and programmering	4	50%	1200	450	5	0.9	1.0	0.2
Stand by until show	24	0%	750	0	18	0	3.6	0.0
Show	4	20%	1200	450	5	0.36	1.0	0.1
Total					28	1.26	5.5	0.3
Price kr/kWh	kr. 2							
Number of lamps	200							
Reduction in energy usage	95%							
Energy saved [MWh]	5.3							
Cost savings	kr. 10 536							

6.6 Ph.D. education

The project has not directly incorporated any Ph.D. education, however the project have had close collaboration to the internal Ph.D. student at DTU Fotonik, Anastasiia Krasnoshchoka and Ada Czesnakowska from Université Toulouse, both on projects on laser lighting. Professor Georges Zissis visited DTU Fotonik as examiner for the Ph.D. Defense of Anastasiia Krasnoshchoka and Carsten Dam-Hansen was examiner for the Ph.D. student Ada Czesnakowska (See section 8.1 for references).

7. Project conclusion and perspective

The conclusions made in the project can be summarized in that

- Experimental investigation and development have shown the large potential of laser lighting technology
- It is possible to make laser diode systems capable of delivering 450 W of laser power to a 4x4 mm2 phosphor material, potentially yielding more than 50.000 lm with appropriate phosphor material
- High power laser lighting systems requires active cooling systems
- It is difficult to illuminate a small phosphor material with high laser power, extract the high emission and actively cool the material
- Phosphor materials have been developed that can emit green, yellow and red light through blue pumping. Efficiencies for green and yellow emission are around 200 lm/W and 50 lm/W for red emission.
- Ceramic phosphors can withstand irradiances up to 50 W/mm^2
- Characterisation of phosphor materials requires a calibrated integrating sphere setup with accurate control of the test laser spot size and power, and the ability to automatically vary these parameters
- Active cooling of phosphor materials is necessary to high power operation and thermal imaging is a vital test tool
- The laser illumination of the phosphor materials has to be very homogeneous in order to avoid hot spots and saturation of the phosphor emission
- Extreme high intensity spot lamps of 25 million cd can be achieved in a Single point LS using available laser lighting components, but with limited luminous flux to around 3500 lm
- Single point LS are limited in light quality in high CCT > 6000 K and low CRI < 70 due to phosphor technology
- Improved color quality is achieved in LiV8 color changeable light system with high CRI range from 3500-5000 K
- Very high luminance of 2100 cd/mm^2 has been achieved exceeding by 20x that of LED technology.
- A direct replacement for a high power HID lamp is a possibility but requires more development in reaching the high luminous flux of more than 30.000-50.000 lm
- It is possible to control and maintain the color output of e.g. the LIV8 color changeable light source using a true color sensor and the developed ACMT algorithm to a level not detectable by the human eye
- It is necessary to establish and have a good collaboration with manufacturers of critical components in order to commercialize the laser lighting technology

The next steps for the developed technology is to

- Do further development of high power laser illumination systems for more homogeneous illumination of the phosphor
- Realize a *Single point LS* with high luminous flux of 30.000 lm to be able to replace HID lamps
- Further develop the LiV8 for efficient color mixing
- Apply for and run research project on phosphor materials for laser lighting
- Do research and development of phosphor materials for red emission
- Do research and development of phosphor materials for higher light quality in color rendering, e.g. combination of green and red emission phosphors
- Design and invention of new laser lighting systems for specific challenging applications
- Apply for and run new development and demonstrations projects on laser lighting with Danish industry

- Benefit from the expected increasing efficiencies and lower cost of laser diode arrays though volume production
- Implement the *ACMT* system for real time color control in BB&S fixtures
- Make the Single point LS into a commercial product for BB&S
- Demonstrate the developed technology at trade shows when these are back in business from the corona restrictions
- Keep educating the lighting industry on the potentials and benefits of laser lighting

The project has shown the large potential of laser based lighting and through extensive dissemination of results for people in both lighting and material research and in the lighting industry, more and more have realized that laser based lighting will be a future key lighting technology that we need to focus on.

There will be a need for more research on phosphor materials for laser lighting. For Denmark this could be a collaboration between DTU Fotonik and Henan Polytechnic University, and there is also a possibility to do European research projects.

In relation to Danish industry the project has resulted in contact to companies working with search and rescue light, and it is expected that laser lighting technology will be able to solve their challenges in achievable luminance and intensity of spot lamps. There will be more development and demonstration projects directed at niche applications and where HID lamps are to be replaced. BB&S will be working on implementing the achieved results from the project in their product portfolio.

There is no doubt that laser lighting will become an efficient lighting technology that will supplement and in certain aspects outperform LED technology. We will in the coming years see more and more applications and products on the market using laser lighting technology.

8. Appendices

8.1 Links and references

- DTU hosts a permanent website for the project at https://orbit.dtu.dk/en/projects/energy-efficient-laser-enhancement-of-stage-spotlights/publications/, this page contains information and links to the journal publications that have been part of the project. As well as other bibliometric information such as downloads, readership and scientific citations.
- many of the activities that has been part of the project can be found here: https://orbit.dtu.dk/en/projects/energy-efficient-laser-enhancement-of-stage-spotlights/activities/.
- Dam-Hansen, C. Munch K., "Status for LED og nye lyskilder", invited talk at Lysets dag 2020: "Lys og de 17 verdensmål", 22-10-2020. https://orbit.dtu.dk/files/238422635/Pr_sentation_Lysets-dag_2020.pdf , video https://youtu.be/rClmC0gUYgA , https://orbit.dtu.dk/en/activities/status-for-led-og-nye-lyskilder
- Demonstration of 25 million candela laser based light source posted on LinkedIn https://www.linkedin.com/posts/andersthorseth_risaeo-dtu-laserlighting-activity-6730019128360345600-SETh
- Krasnoshchoka, A. (2019). Diode laser based lighting. Technical University of Denmark. https://orbit.dtu.dk/en/publications/diode-laser-based-lighting
- Ada Czesnakowska. Development of white light source based on laser diode and suitable phosphor. Electric power. Université Paul Sabatier - Toulouse III, 2018. English. NNT: 2018TOU30180. tel-02325596 https://tel.archives-ouvertes.fr/tel-02325596/document

8.2 Abbreviations and symbols

ACMT	Active Color Management Technology
CCT	Correlated color temperature
cd	Candela (SI-Unit)
CIE	International Commission on Illumination / Commission Internationale de l´Eclairage
CRI	Color rendering index
EPFL	École polytechnique fédérale de Lausanne
HID	High-intensity discharge (lamp)
IEA	International Energy Agency
LED	Light-emitting diode
lm	Lumen (SI-Unit)
SMD	Surface mounted device