LED spectrum optimisation using steady-state fluorescence gains

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Abstract

The use of light emitting diodes (LEDs) in greenhouses entails the possibility to control the light in a better way, since both spectrum and light intensity can be adjusted. We aim at developing a method to automatically find the optimal spectrum in terms of energy consumption and plant growth. Previous work shows that chlorophyll fluorescence (ChlF) at 740 nm strongly correlates with the photosynthetic rate (carbon dioxide uptake rate) and that the net efficiency of a LED group therefore is coupled to the fluorescence gain w.r.t. energy consumption, i.e., the slope of a curve depicting steady-state ChlF versus applied power to the LED group. In the present work we compare the fluorescence gains for six different LED types (wavelength peaks from 400 to 660 nm) and six different species: tomato, cucumber, basil, lettuce (two species) and dill. We also compare two different kinds of experiments: steady-state experiments, waiting for the fluorescence to reach a steady state at a few incident light intensities, and ramp experiments, where the light intensity is increased slowly. The ramp experiment gives essentially the same information as the steady-state experiment, but was found to slightly overestimate the gains of the blue LEDs. Being aware of this, it should be possible to initially use the faster (ramp) method in order to find the right light composition, possibly using steady-state experiments for a few LED colours to fine tune the lamp. The relative order of the fluorescence gains among the tested LED groups is similar, but not identical, for all species tested. LED660 has the highest fluorescence gain w.r.t. incident photon flux density, and LED400 and/or LED530 have the lowest. However, the important quantity is in fact the fluorescence gain w.r.t. applied electrical power. If the individual electrical efficiencies of the LEDs change the most efficient power split on the different LEDs might change.

Keywords: optimal light spectrum, light emitting diode (LED), fluorescence gain, chlorophyll fluorescence, photosynthesis, greenhouse illumination

INTRODUCTION

The illumination in greenhouses is dominated by high pressure sodium (HPS) lamps that are generally controlled manually by on/off control. Changing to light emitting diodes (LEDs) entails an energy saving potential (Singh et al., 2015), due to higher electrical efficiency of many LEDs compared to HPS lamps. Combining different LEDs, also enables control of the spectral distribution of the light, which could potentially reduce the energy further. Many studies have been conducted that investigate the spectral effect on plant growth, commonly by comparing the impact that various light sources, and in particular their ratio among blue, green, and red light, have on the growth of different plant species during their life cycles, e.g., Ouzounis et al. (2015), Cope et al. (2014), Massa et al. (2008), Kim et al. (2004), Dougher and Bugbee (2001). There are also a few studies on the use of LEDs as supplement to sunlight in greenhouses (Hernández and Kubota, 2012, 2014).

The optimal energy split of the applied power among the different LED colours could possibly depend on a number of factors, such as plant species, required characteristics of the plant, available LED groups and their electrical efficiency. The aim of the work presented here is to automatically find the optimal spectrum based on a remote measure of growth.

The idea is that for the specific crop being cultivated, bounds on the ratios of different colours (for example between blue, green, and red wavelengths) have been specified to guarantee morphologically healthy and high producing plants. However, within these bounds we aim to use the power split that maximizes the growth for a given applied electrical power P_{tot} (Figure 1). In order to do so, a measure of the growth rate on canopy level is needed. Here, we have focused on finding an indirect proxy marker for photosynthesis by measuring chlorophyll fluorescence (ChlF).

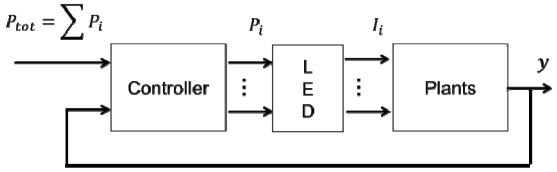

Figure 1. A schematic picture of our aim; developing a method to automatically find the energy optimal split of the applied power P_{tot} among the available LED groups. The fluorescence gain (i.e. the slope of a curve depicting steady-state ChlF versus applied power) is the candidate signal y to be used in the feedback loop.

In a previous study on basil (Ahlman et al., submitted) the potential of using top-of-canopy steady-state ChlF at 740 nm as a measure of growth rate was investigated. Although the relationship between ChlF and photosynthesis is complex in general, and the ChlF signal is convoluted by structure on a canopy level, a strong nearly linear relationship between steady-state ChlF and photosynthesis (measured as carbon dioxide uptake on leaf-level) was observed on healthy plants subject to a large number of PAR light intensities (Figure 2). This simple relationship may be attributed to the correlation between ChlF and absorbed PAR, which in turn is closely related to photosynthesis in healthy plants, as has been discussed by others (Guanter et al., 2014). As a consequence of this relation Ahlman et al. (submitted) and Wik et al. (2014), showed that the (short term) efficiency of one LED group relative to another is directly related to the fluorescence gain, i.e., the slope of a curve depicting steady-state ChlF versus the applied power to the LED group. The intuitive interpretation is that if you want to increase the lamp power you should use the LEDs that increase the steady-state ChlF the most. Conversely, if the lamp power is to be decreased one should decrease the power to the group that decreases the fluorescence the least.

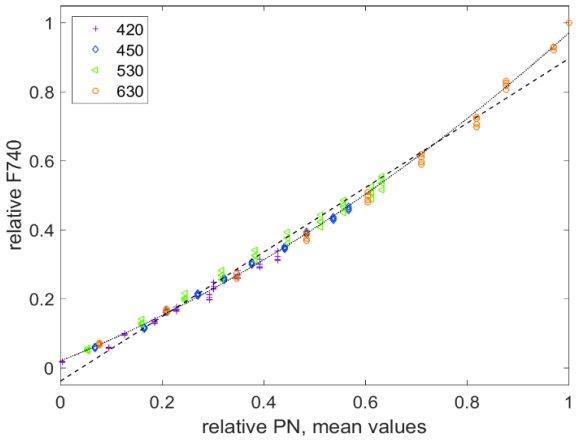

Figure 2. The relative fluorescence at 740 nm (F740) versus the relative photosynthetic rate (PN), i.e., CO_2 uptake rate, measured by an infrared gas analyser on leaf-level. One LED group was used at a time, with light intensities up to 350 µmol m^{-2} s^{-1}. Dashed line shows a first order curve fit (R^2=0.982) and the solid line shows a second order curve fit (R^2=0.996). Data from Ahlman et al. (submitted).

In the investigation by Ahlman et al. (submitted) red photons were found to be best in terms of photosynthetic efficiency (mol CO_2 mol^{-1} incident photons), but after taking the photon efficiencies of the LEDs (ratio of photon flux to electrical power) into account some blue LEDs were equally efficient as the red LEDs. It was also found that the photosynthetic efficiency depended on the light intensity to some extent. Since the photon efficiency changes with temperature and age, remotely sensed ChlF could potentially be used to calibrate a lamp to optimal photosynthetic efficiency (within the ratio-bounds specified for the plant). In order to assess the potential use, a number of different plant species have now been investigated, namely tomato, cucumber, basil, lettuce (two types) and dill. Using a lamp equipped with multiple LED groups the ChlF gain was measured for six different colours ranging from 400 to 660 nm (peak wavelength). For a calibration to be conducted within reasonable time, a fairly short time can be spent on determining the gain of each LED colour, which means that the steady-state fluorescence can normally only be determined for a few light levels. Since it was found that the gain changes somewhat with intensity, and possibly to the extent that the order of the LEDs in terms of efficiency may change, it is desirable to have more densely gridded information. Therefore, the possibility to use the ChlF when each LED colour is slowly ramped, instead of steady-state ChlF for a few intensities, was also investigated.

The main outcome of this investigation is that the results are similar, but not identical, for all species tested. LED660 has the highest gain per incident photon and LED400 and/or LED530 has the lowest. However, it has to be kept in mind that the relevant quantity is in fact the gain per applied electrical power, which is highest for LED660 followed by LED450 and LED420. Using ramp experiment instead of steady-state experiment seems to slightly overestimate the efficiency of blue LEDs (or underestimate red ones).

MATERIALS AND METHODS

Plant species and growth conditions

A number of species were studied, tomato (*Solanum lycopersicum* F_1 'Lizzano'), cucumber (*Cucumis sativus* F_1 'Max'), basil (*Ocimum basilicum* 'Aroma 2'), two types of lettuce (*Lactuva sativa* 'Black seeded Simpson' and 'Galiano') and dill (*Anethum graveolens* 'Ella'). All plants were grown in a controlled environment (16 h photoperiod and 23/17°C day/night temperatures) at Heliospectra Plant Lab under LED lamps (LX602G, Heliospectra, Sweden), having three diode types; blue (450 nm), red (660 nm) and white (5700 K), and the light intensity at plant level was set to 280 µmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) for tomato, and 160 µmol m^{-2} s^{-1} for the others. The light spectrum contained approximately 20% blue (400-500 nm), 10% green (500-600 nm) and 70% red (600-700 nm) light. Most of the samples were grown under other, but similar, light in the beginning of their growth cycles.

The experiments were conducted 3-6 weeks after seeding, except for tomatoes which were almost four months old.

Experimental unit

All experiments were carried out in an experimental unit, 0.5×0.7 (m), delimited with reflective curtains (silver/white Diamond Diffusion Foil, Easy Grow, UK). Two LED lamps (RX30 Heliospectra, Sweden) were placed above the experimental unit. Six different LED groups were used, having peak wavelengths at about: 400, 420, 450, 530, 630, and 660 nm (Figure 3), and relative photon efficiencies (photons per applied electrical energy) of: 0.38, 0.60, 0.66, 0.27, 0.26, and 1.00, respectively, at maximum intensity of the individual LED groups.

The light was detected by two spectrometers (Maya 2000 Pro Spectrometer, Ocean Optics, US) each equipped with a 600-µm optical fibre. One was placed at canopy level, measuring the incident light, and having a cosine diffuser giving a field of view of 180°. The distance from the lamp to the canopy level was approximately 0.5 m, but differed slightly due to plant size. For the tomato, which was significantly higher than the other plants, the

height of the experimental unit was modified to retain the same distance between lamp and canopy. The other spectrometer was placed between the lamps and facing the plants to detect the fluorescence signal. In order to only measure green area, the field of view was delimited to about 25°.

The temperature throughout the experiments was 23±1°C (measured in the luminaire), except for when LED530 was used, the temperature then increased 2°C due to the lower electrical efficiency of those LEDs.

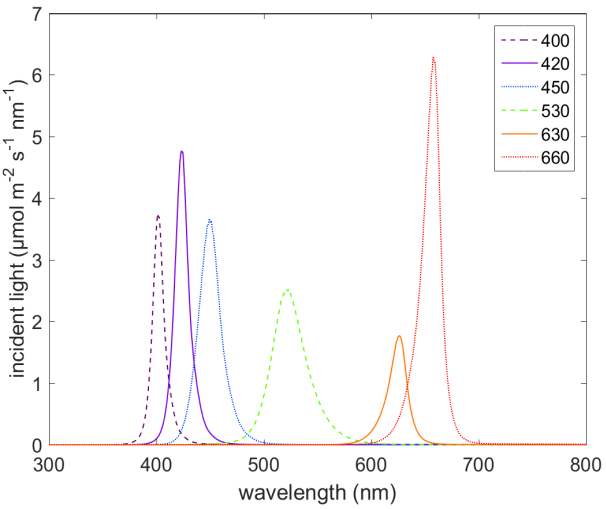

Figure 3. Incident light spectra, using one of the six LED groups at a time. In the analysis the incident light has been integrated from 350 to 700 nm, in order to capture all light.

Light scheme

During one experiment all six LED groups were used, one at a time, starting with LED400 and continuing in the order of increasing peak wavelength. Two different kinds of experiments were tested, steady-state experiments and ramp experiments.

In the first set of experiments each light level was held for 9 min, in order to reach (close to) steady-state fluorescence. Three light intensity levels (in increasing order; based on the capacity of the specific LED group; shown in Figure 4) were tested for each LED group. The second set of experiments (conducted on all plant species except lettuce 'Galiano' and dill) aimed at investigating if the same information (differences in fluorescence and fluorescence gains between the different LED groups) could be found without awaiting steady-state. The light was then held at a constant low level for 2 min, whereupon the light was slowly increased during 2.5 min, while the fluorescence and the incident light were measured at 25 different light intensity levels in total. The range spanned by the ramp was normally around 80 µmol m^{-2} s^{-1}, but differed depending on the capacities of the LEDs (from 35 µmol m^{-2} s^{-1} for LED630, to 140 µmol m^{-2} s^{-1} for LED660; see Figure 4).

Data processing

In the analysis the incident light, measured in µmol m^{-2} s^{-1} has been integrated from 350 to 700 nm, in order to capture all light energy, including the LED having peak wavelength at 400 nm (Figure 3). The fluorescence signal, also measured in µmol m^{-2} s^{-1}, is the integral over the peak from 735 to 745 nm.

After one experiment, the plants were moved from the experimental unit in order to make room for the next plant species. The steady-state and ramp experiments for each species were done with a maximum of one day in between.

In order to compare experiments (between species and also experiments on the same species performed on different occasions), the signal needs to be normalized, since the

fluorescence signal is sensitive to for example the distance between plant and spectrometer, and to the geometry of the plants. All values in one experiment were therefore normalized with the same factor so that the fluorescence gain for LED660 equals one for the case when a straight line was fitted by least squares to the data. When a polynomial of degree two was fitted to the data (only for ramp experiments), the fluorescence gains varied with light intensity, and the normalization was done so that the mean value of the fluorescence gain for LED660 equals one.

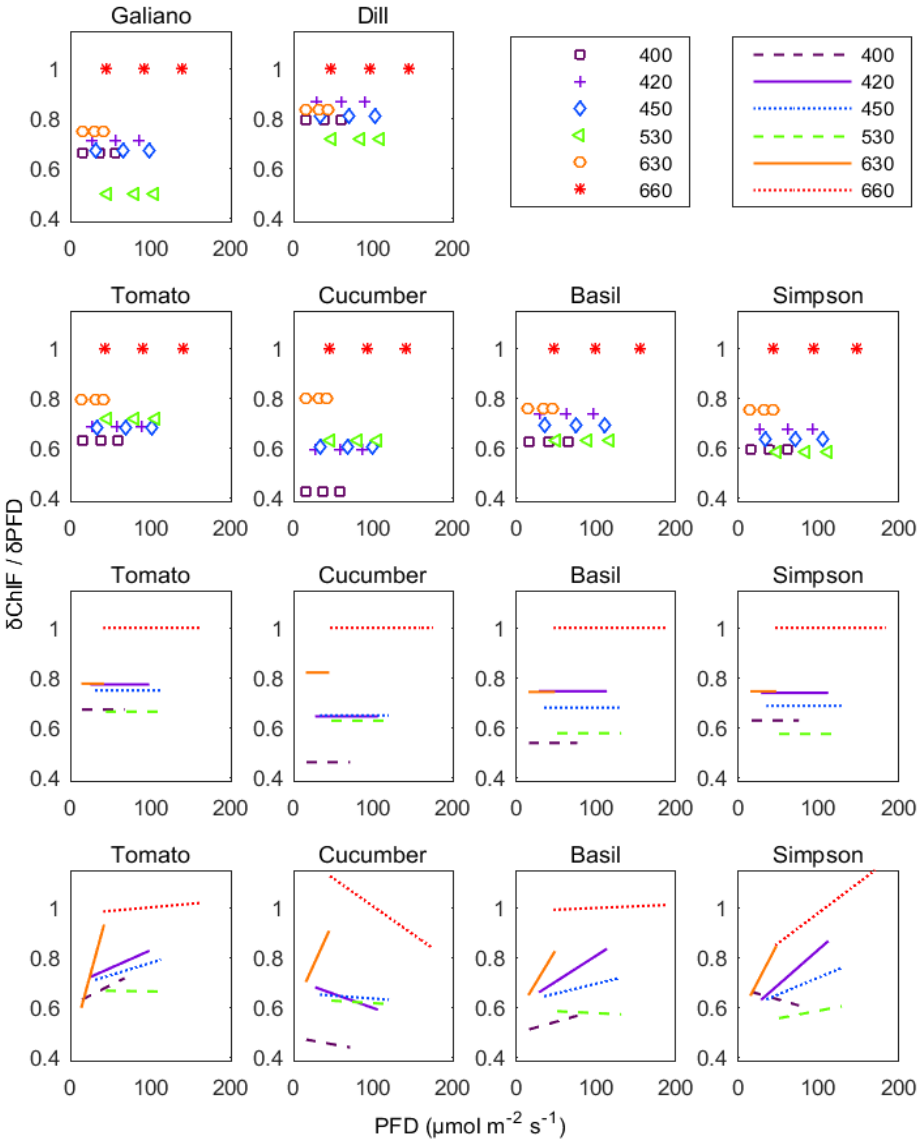

Figure 4. Normalized fluorescence gains w.r.t. PFD, i.e., the slope of steady-state ChlF (photon flux integrated from 735 to 745 nm) to incident PFD, versus incident PFD integrated from 350 to 700 nm. Steady-state experiments are presented in the first two rows. The fluorescence measured for three incident light intensity level for each LED group and the gains are calculated from a line fitted to the data. Results from the ramp experiments are presented in row three and four; first the gain when a first order polynomial is fitted to the data (row 3; R^2-adj >0.99) and then when a second order polynomial is fitted to the data (row 4; R^2-adj >0.99). Each set is normalized such that the mean value of the fluorescence gain is maximum 1 (always maximum for LED660).

RESULTS AND DISCUSSION

Steady-state experiment

For all species tested, LED660 gives the significantly highest fluorescence gain w.r.t. incident photon flux density (PFD) compared to the others (Figure 4, first and second row). LED630 gives the second highest gain for all species except for dill, where it is on par with the blue LEDs. Next is LED420, closely followed by LED450, and the least efficient of the blue ones is LED400. For dill and lettuce 'Galiano', LED530 gives the lowest gain, while for cucumber and tomato LED530 performs slightly better than all the three blue LEDs. For lettuce 'Simpson' and basil, LED400 and LED530 have the same (and the lowest) gain.

This is essentially similar to the spectral effect of CO_2 uptake that McCree measured on small leaf sections of 22 different plant species (McCree, 1972). One peak was noted in the red light region and a second, normally a bit lower, peak in the blue light region. Depending on species the peak varied, both spectrally and in relative intensity. The distinct difference between the two red diodes (LED660 and LED630) observed in our experiments, could, however, not have been predicted by looking at McCree's results.

The largest relative differences in gains are observed for cucumber. After LED660, LED630 had the highest significantly gain and LED400 the lowest. For all other species the five LED gains (LED660 not counted) are fairly close to each other. This means that per incident photon the differences in output (fluorescence or photosynthetic rate) are small for all species tested. This indicates that differences in photon efficiencies, from applied power to photon flux, are crucial when aiming for the highest photosynthetic rate for a given applied power, which is confirmed in Figure 5 showing that LED660 followed by LED450 and LED420 have the significantly highest gains w.r.t. electrical power.

Ramp experiment

1. First order polynomial fit.

Measuring the fluorescence and fluorescence gains without awaiting steady-state, (but slowly increasing the light intensity, see Figure 4, third row) gives essentially the same results as the steady-state experiments. LED660 still has the highest fluorescence gains for all species tested (lettuce 'Galiano' and dill were not included in this setup), the other LED gains are lower and closer to each other and LED400 and/or LED530 have the lowest gains. Cucumber is still the species where the differences are most pronounced, with LED630 higher, and LED400 lower than the other blue and green ones. An interesting difference, though, between the steady-state experiment and the ramp experiment, is that in the latter one of the three blue LEDs seems to be slightly overestimated compared to the others (or the red LEDs are underestimated), resulting in no difference in gains for LED630 and LED420 (except for cucumber).

2. Second order polynomial fit.

An advantage with measuring the output at several different light intensities (in the ramp experiments the fluorescence was measured at 25 light intensity levels, compared to three levels for steady-state experiments), is that it allows a fit of a model of higher order. The 4th row in Figure 4 shows the fluorescence gains from the ramp experiments, when a second order polynomial is fitted to the data.

As can be seen, some of the gains intersect with each other. The corresponding intensity levels can be interpreted as levels where the relative efficiency of the LEDs changes order. For example, for tomatoes the gain for LED420 and LED630 intersect at approximately 20µmol m^{-2} s^{-1} indicating that LED420 may be more efficient than LED630 below that intensity level. Note that including the specific photon efficiency of each LED group in the analysis will change both the magnitude and the slope of the individual gains such that the levels of intersection also may change (not included here).

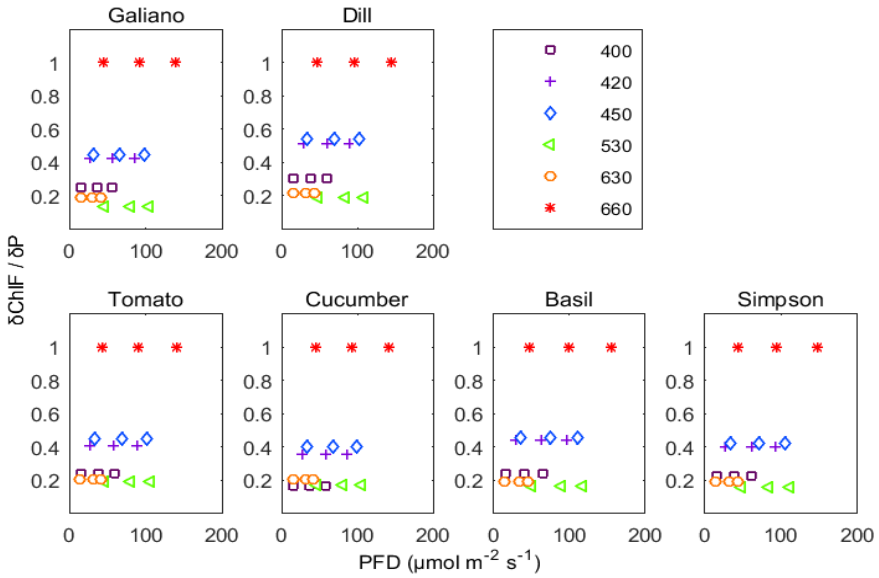

Figure 5. Normalized fluorescence gains w.r.t. applied electrical power as a function of PFD for the steady-state experiments. The fluorescence gains are calculated by multiplying the fluorescence gains w.r.t. PFD (Figure 4) with the photon efficiency of each LED group, respectively. The photon efficiency was measured at maximum intensity of the LED group and is assumed to be constant.

Intersection of the fluorescence gains of the three blue LEDs (400, 420 and 450), which are obtained for some of the sets, indicates that even for a predefined blue to red ratio, the optimal power split within the blue LEDs differ depending on the light intensity.

The slope of the gain for LED630 is significantly higher than for LED660, indicating that (if the gains can be extrapolated) for high light intensity LED630 could be more efficient than LED660. Though, it cannot be precluded that part of the reason for the different shapes, is that the incident light for LED630 and LED660 differ significantly, up to about 45µmol m^{-2} s^{-1} for LED630, and only above that for LED660.

CONCLUSION

For all plant species investigated, i.e., tomato ('Lizzano'), cucumber (F_1 'Max'), basil ('Aroma 2'), lettuce ('Black Seeded Simpsons' and 'Galiano') and dill ('Ella'), the fluorescence gain w.r.t. incident PFD was highest using LED660. For the other five LEDs (400, 420, 450, 530 and 630) the differences were smaller but LED400 or LED530 were always lowest, which is not surprising considering that part of the LED400 spectrum is outside the normal PAR range and the dip in quantum yield and absorptance in the green waveband (McCree, 1972). Cucumber is the species having the largest differences in the fluorescence gains. Notice, though, that in terms of overall efficiency the relevant quantity is the fluorescence gain w.r.t. applied electrical power, which was highest for LED660 followed by LED450 and LED420 as these LEDs are the most efficient in the lamp being used. If the electrical efficiency of the individual LEDs changes, due to for example different operating conditions or degradation over time, the result might differ.

Slowly increasing the light intensity and measuring the fluorescence increase (ramp experiment) gives essentially the same relative gains as if awaiting steady-state for a few light intensity levels. One difference noted, though, was that the ramping tends to slightly overestimate the output from the blue LEDs. Having several measurements allows a fit of a curve of higher order (second order polynomial fit was tested for ramp experiments), giving fluorescence gains that varies with intensity level. The results indicate that depending on light intensity level the optimal power split might vary.

The experimental time differed significantly between the two types of experiments;

the ramp experiment took only 1/6 of the time for the steady-state experiment. One needs to be aware of the slight difference in result that did exist, but the time saving would probably justify the use of ramp experiments. Ideally, fast measurements (like ramp experiments) could be used to find an initial approximation of the optimal light at current conditions. Further steady-state experiments could then be used to tune the settings for LEDs having similar gains.

Ongoing research is carried out to investigate if the method and results can be translated to the situation where a combination of LEDs are being used.

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