\chapter{Rainbow Measurements}\label{ch:7 Rainbow Measurements}

Abstract

\section{Introduction}\label{ch:6 Rainbow Measurements: Introduction}

In current matched vertical tandem stacks, solar cell characterization has commonly been performed in a similar manner as single junction PV characterization, where the JV parameters are extracted from the JV curve obtained from the simultaneous measurement of the entire vertical stack. On the other hand, multi-terminal vertical stack tandem solar cells, where each individual sub-cell is electrically isolated, are characterized in a similar manner. In such cells, a separate JV curve is measured for each individual sub-cell, and then the resulting efficiency is simply added together.

This is an optimal characterization procedure, taking into account the spectral limitations associated with vertically stacked tandem solar cells, where the illumination spectral distribution of the bottom sub-cells is strictly dictated by the absorption range of the sub-cells above. In such a stack, the illumination conditions of each sub-cell are completely fixed, so the efficiency can be obtained with a single set of JV curves. In a similar manner, beam splitting tandem technologies have been using a similar characterization procedure, where high EQE values guarantee that optimal performance will be achieved when the dichroic mirror cutting wavelength is equal to the absorption tail wavelength of the higher $E\_g$ sub-cell.

% Figura en la que hi hagi una optimal dividing wavelength super obvia i una altre que diguis what aqui enserio?

On the other hand, the concept of RAINBOW solar cells requires a more versatile method to assess their performance and optimal dividing wavelength. That is because this concept is oriented towards the field of solution processable photovoltaics, in particular OPV, where the EQE curve of each sub-cell is not ideally shaped, resulting in unintuitive combinations (figure x). Besides, the wide availability of ever increasing photoactive materials, with band gaps widely spread throughout the entire solar spectrum, requires the use of a systematic approach to evaluate the performance and the optimal dividing wavelength of all possible RAINBOW combinations. That is why, based on the simulations and calculations performed on the previous chapter, we designed and constructed an experimental setup capable of generating custom illumination spectra that can be used to characterize RAINBOW solar cells. This setup was fully designed and developed in collaboration with soon to be doctor Miquel Casademont.

\section{SOLS Setup}\label{ch:6 Rainbow Measurements: SOLS Setup}

\subsection{Concept and Construction}\label{ch:6 Rainbow Measurements: SOLS Setup: Concept and Construction}

% Parlar del LED simulator i dir que no mola tant com nosaltres

In order to characterize RAINBOW solar cells we focused on building an experimental setup, capable of emulating the conditions of the python model discussed in the previous chapter. For that, we need a way to illuminate a solar cell with a specific fraction of the solar spectrum, accurately controlling it and being able to perform systematic modifications, while simultaneously measuring the solar cell's performance. To do so, we designed an experimental setup that accurately filters the spectrum by spatially separating it onto a dynamic mask, which blocks specific wavelength components, and then recombining it again into a homogeneous light spot. With this contraption we are able to generate any Spectrum On-demand from a given Light Source (SOLS), giving us the name of the setup. The resulting SOLS setup, is able to convert any solar simulator into a RAINBOW characterization station, being able to emulate the conditions of the previous chapter simulations in a real measurement.

% Figure with the schematic view of the sols drawing

% The SOLS setup consists of several parts, schematically represented in figure x, which we will discuss in detail in the following paragraphs, in a logical order that does not necessarily coincide with the light path. The first part on the incoming light path is a diffractive element that spatially separates the colours, which in this embodiment is depicted as a type of dispersive prism known as an Amici prism. In this case, spectral separation arises from the refractive index wavelength dependence, which results in different colour light components being refracted at different angles. The main advantage of the Amici prism is that, with a clever arrangement of prisms with different diffractive properties, great wavelength separation can be achieved without a significant change in optical axis, defined by the prism central wavelength (fig x).

% Maybe figure of an amicii prism dispersion

% In order to spatially filter the spread solar spectrum, as a first approximation for this embodiment, we devised two solutions that, when simultaneously implemented, allowed us to dynamically and accurately control the spectral output of the SOLS. The first solution, consists on an accurately shaped static mask that, when placed in the spatially separated light spectrum, modulates the relative spectral intensities to fully conform the output spectrum to the sun's spectrum, resulting in an X solar simulator in these regions (figure miquel lo bo que es el sols). With their small fins, these masks partially block certain parts of the spectrum, reducing the intensity of those specific wavelength components, finely tuning the spectral shape. We can quickly see that, with this filtering mechanism, the spectral filtering resolution is directly proportional to wavelength dispersion. Because of that, we tried to spread the colours as much as the experimental setup allowed for.

% Figure data miquel per veure que aconseguim que el sols sigui un solar simulator dabuten

% After the static spatial masks, the second solution allows us to dynamically filter the spectrum, emulating the conditions of the previous chapter simulations. In order to divide the spectrum in two parts in a systematic manner, we used two motorized guillotines that laterally block a variable portion of the spectrum (figure x) to create the ``red fraction'' or the ``blue fraction''. These guillotines can be operated separately, to emulate the behaviour of a dichroic mirror, or simultaneously, to obtain narrow band spectra for higher junction RAINBOW solar cells. Being motorized, we could accurately control the position of the guillotines in a highly repeatable way, laterally filtering the spread light into neatly cut spectra (figure x figura de is amicii truly our friend amb tots els talls no?), especially within the visible range.

% Figure explaining the cutting of the guillotines and the resulting spectrum and how that correlates with the simulations somewhow

% We want to note that, these spatial filtering solutions are just a first approximation to mechanically filter the spectrum in this particular embodiment. There is a wide range of better, more complex solutions, that will be implemented in future versions of the SOLS setup. These approaches integrate the static spatial masks and the guillotines in one solution, able to filter the spectrum with wavelength independent intensity resolution in real time to create any desired spectrum, introducing closed feedback loops that can correct spectral and intensity variation and drift in the light source. The best candidates for this job are Liquid Crystal Displays and Digital Micromirror Devices, which are able to spatially filter an incoming light source with great speed and resolution.

% LCD /DMD figure with fully custom spectra

% To remix the dispersed colours, we needed a way to counteract the colour dispersion introduced by the Amici prism, so that the different wavelengths converged on one single spot. In this embodiment, we used a very wide custom curvature cylindrical mirror, that was big enough to redirect the widespread colour beam into a focal point. Such a big custom mirror was not easy to find commercially unless custom made, which for prototyping purposes, without accurate manufacturing dimensions was not a good idea, so we built it ourselves. After a significant amount of trial and error, we ended up with a rather nice 3D printed first surface mirror, with a custom curvature and corrosion protection, further details of the construction can be found in appendix x. By combining this mirror with a vertical cylindrical lens, we were able to reconcentrate the light into a small 7x5 mm spot, an area slightly bigger than our solar cells.

% Mirror Picture with rainbow colours

% The main problem with this reconcentration strategy was that this spot still had spectral homogeneity problems. Being separated, even though the colours were reconcentrated by the mirror into a small spot, upon laterally filtering with the guillotines, the width of the spot decreased linearly with the filtering. This posed a serious problem, since most cells operate best under homogeneous lighting conditions. To solve that issue, we devised a simple yet effective contraption that combined a light diffuser placed on the focal point of the mirror and a light pipe that homogenized the disperse light coming out of the diffuser. On the light pipe output, after all colours have thoroughly mixed, the spectral homogeneity of the beam is outstanding (figure x). For more information on the light pipe assembly and design, the reader is referred to appendix x.

% Picture of the light before and after the light~pipe

% The resulting SOLS setup is a really powerful spectral shaper, capable of outputting completely custom spectra with a given input spectrum. As a fun, food analogy, we can compare the SOLS with a cookie cutter, where as long as your light source spectrum (dough) is wider and taller than your desired output spectra (cookie cutter shape), the SOLS will be able to reproduce it. In figure x we can see some of the first approximations to fully custom spectra with the current embodiment.

% ficar spectra weird shapes for shits and giigles anar un dia a l'icmab i intentar fer coses random per posar a la tesis. Always plot the original fully open spectrum for comparison with the different shapes (if it works nicely)

% We want to note, however, that the SOLS setup still has still plenty of room for improvement in many aspects. On one hand, being the first iteration, its spectral shaping capabilities are still far from perfect, as we can see in figure x, where the spectral cut is not perfectly sharp. On the other hand, this first embodiment is still not able to perfectly reproduce the optimal RAINBOW conditions, due to a lack of concentrating power. As we stated in the previous chapter, in a RAINBOW solar cell, the solar spectrum is redistributed among the sub-cells, spectrally concentrating the power into various wavelength regions. In order to reproduce such conditions, we need a high degree of concentration, dictated by the smallest wavelength range we want to measure; higher concentration leads to higher wavelength range resolution. This first embodiment, however, is limited to the first approximation used in the previous chapter simulations, where the spectrum is not concentrated and only divided between the two sub-cells. This first step has been necessary in order to validate the results from the previous chapter, and to pave the way for the following iterations of the SOLS setup, providing us with a quick and reliable method for the \textbf{determination} of useful tandem combinations.

\subsubsection{Wavelength Sweep Types}\label{ch:6 Rainbow Measurements: SOLS Setup: Concept and Construction: Rainbow Sweeps}

% The lateral spectral filtration used in the SOLS setup, to emulate the simulation conditions, introduces a series of concepts we need to discuss in order to understand the operation of this experimental setup. The first thing to notice is that, with this setup we are not measuring the two sub-cells simultaneously by dividing the spectrum, as we did in the simulations. Rather we are measuring one sub-cell at a time with its spectral fraction, discarding the remaining fraction, which in the simulations would be redirected to the other sub-cell. As a result, the measurement is divided in two sub-measurements, one for each sub-cell. This sub-division means that we can either illuminate the sub-cell being measured with the ``red fraction'' of the spectrum, while the ``blue fraction'' is being blocked by the guillotine, or with the ``blue fraction'', with the ``red fraction'' being blocked (figure x). We have consequently named these two procedures, a ``red sweep'', when we illuminate the cell being measured with the ``red fraction'' of the spectrum, or a ``blue sweep'' when using the ``blue fraction''. Even if this sub-division doubles the number of measurements, it is really advantageous because we can scan each cell treating it as the ``red'' or the ``blue'' cell, without having to physically combine the measurement with another sub-cell. These measurements are later combined using software to evaluate the RAINBOW performance of any sub-cell combination, just with the individual measurements of each sub-cell.

% Figure comparing the simulations, with the figure in the simulations where the spectrum i s divided in two and given to each of the cells, with the SOLS measurement procedure, where one part of the spectrum is cut and the other used to illuminate the cell, with a red sweep and a blue sweep.

% This measurement procedure also introduces another less crucial concept, related to the fact that the wavelength sweep can be performed in two different ways. We can either begin the measurement by blocking entire spectrum, gradually adding light as the sweep progresses, called an ``opening sweep''. Or we can do the opposite, and start with the entire spectrum, gradually removing light as we move the guillotine, called a ``closing sweep''. Combining these two concepts, results in 4 sweep types: blue opening sweep, blue closing sweep, red opening sweep and red closing sweep. The opening/closing sweep factor might seem unimportant at first, however it can have significant effects in phenomena such as UV photoactivation or UV driven degradation. As an example, in the case of ``red sweeps'', it might be more interesting to perform a ``red opening sweep'' to expose the cell to as little UV as possible during the measurement, to minimize degradation.

% A small curieosity is that, the motors that move the guillotines have the name of the part of the spectrum they block, the ``red motor'' being the one that moves the guillotine that blocks the ``red fraction'' of the spectrum and vice-versa. However, since we are blocking the spectrum, to perform a ``red sweep'', we will have to move the ``blue motor'', since the ``blue fraction'' of the spectrum is the one that has to be blocked.

\subsubsection{Dividing Wavelength Calibration}\label{ch:6 Rainbow Measurements: SOLS Setup: Concept and Construction: Dividing Wavelength Calibration}

% To perform RAINBOW measurements, we needed a way to correlate the position of the motors with the dividing wavelength of the output spectra. To do so, we measured the SOLS output spectrum for every possible guillotine position. The resulting spectra, however, were not as sharply cut as those on the simulations, because of imperfections on wavelength separation, which were especially pronounced on the NIR range (figure x). To account for such imperfections, we fitted a sigmoid curve for each filtered spectrum, and calculated an effective dividing wavelength for each motor position. From these calculations we obtained a direct correlation table between motor position and calculated dividing wavelength, greatly simplifying motor operation. In order to ensure the reliability of this calibration, we measured the output spectra for both a ``red sweep'' and a ``blue sweep'' on the same dividing wavelength, added them them together, and compared the resulting combined spectrum with the sun spectrum. The resulting spectrum is almost exactly equal to the solar spectrum, hence we can assure that the dividing wavelength for a ``red sweep'' and for a ``blue sweep'' are perfectly complementary, indicating that our fitting method was accurate in dividing the spectrum in two equal parts, even if the division was not a perfect step function.

% (figura que adds the two spectra and results the solar spectra for various div wavelengths.)

\subsubsection{Cell XYZ Stage}\label{ch:6 Rainbow Measurements: SOLS Setup: Cell XYZ Stage}

% In the current embodiment of the SOLS setup, in order to measure a solar cell, we need to place it in direct contact with the end of the light pipe, to guarantee constant lighting conditions. In the particular case of our 24 pixel substrates, during the measurements, we also required to electrically contact each cell on the substrate, one by one for each JV curve. On top of that, measuring the power output of the light~pipe to calculate the cell efficiency is an essential step, as well as the measuring the spectrum to make sure the output is consistent with the solar spectrum. Because of the requirement to move a considerable amount of detectors and cells in and out of the light pipe, we immediately decided that a motorized stage was crucial. Nonetheless, since the ones available in Thorlabs did not provide enough movement range at a reasonable cost and ease of implementation, we decided to design and build our own.

% Picture of the XYZ stage in general and then picture of the light~pipe being inserted in each and every sensor.

% The resulting motorized stage consists of a main carriage, mounted on a custom made XYZ stage, similar to that used in the EQE setup, but with an extra coordinate to be able to move in the Y direction to approximate the detectors and the cell in and out of the light~pipe. The main carriage holds a Pika demultiplexer board, a thermopile, and a Thorlabs lens and fiber optic coupling, connected to a flame spectrometer. The Pika demultiplexer is held on the carriage with magnets so that changing the cell is easier, while maintaining positional accuracy, making sure the cell is always in the same position after placing the Pika board back on the main carriage.

% While this motorized stage is technically not an intrinsic part of the SOLS setup, it has proven to be crucial to reliably measure our particular solar cells. Besides, it allowed us to perform extremely long experiments with careful calibration on each measurement and with high repeatability.

\subsection{Software and operation}\label{ch:6 Rainbow Measurements: SOLS Setup: Software and operation}

%Potser ficar imatges petites de tot el proces no?

% The entire RAINBOW measurement procedure, requires the presence of some kind of director that is able to precisely control all the instruments, sensors and actuators, while at the same time gathering, processing and saving all the data generated on every measurement. To achieve this arduous task, we have developed a powerful piece of software that acts as the main brain of all RAINBOW measurements, relieving most of the hard work from the user for headache free measurements. The software was developed on LabVIEW NXG because of its intuitive graphical user interfaces that make user interaction really simple, and because it is an intuitive programming language in which we had already developed several instrumentation libraries, to control devices such as the Keithley SMU or the Thorlabs photodetectors.

% Small scheme with each and every Instrument controlled by the software and what does it perform as well as some of the tasks of the software with inputs and outputs.

% To make a fully functional software capable of handling all possible scenarios, we programmed more than 600 subroutines that spread along x different tabs, which provide various functionalities, from regular measurements to calibration procedures and software debugging. Besides the main software, we also had to develop several additional libraries, in order to control the Thorlabs motors and the Flame spectrometer, since they had not yet been developed for this version of LabVIEW.

% To get a sense of the complexity of one single measurement and to further understand the equipment, let us run through the entire measurement procedure step by step:

% The first step in any measurement consist on turning on all the necessary equipment, and leaving the solar simulator on for at least 10 min to ensure a stable spectrum, before starting the measurements. While the spectrum stabilizes, we detach the Pika demultiplexer board from the main carriage, where we place our substrate containing the 24 cells, and then re-attach it with the magnets. At this point, our interaction with the SOLS hardware comes to an end. This limited interaction with the hardware makes for a user friendly equipment that only requires the user to change the sample, with the equipment taking care of everything else.

% Figure of the front panel that shows all the controls of a rainbow measurement

% Referenciar tots els intstruments a l'esquema (ficar labels)

% With substrate is in place, we select all the parameters necessary for our RAINBOW measurement. These are related to the various aspects of any RAINBOW measurement, and are divided in x parts: (DESCRIBE HERE ALL THE PARAMETERS MORE OR LESS) also cell selection

% The measurement starts by homing the main carriage, for positional accuracy, and then moving it so that the thermopile is carefully placed in front of the light~pipe. This way, we are able to measure the power output of the SOLS setup for calibration and calculation purposes, since every efficiency measurement is normalized with the total spectral power. After that, the thermopile is slowly retracted away from the light~pipe, and the carriage moves so that the first selected cell is placed directly in front of the light~pipe. With the cell in place, the spectral filter guillotines move to their starting position, depending on the type of sweep, and then they move to the first dividing wavelength position. Once illuminated with the right spectrum, the software instructs the Keithley to take the first JV curve at that dividing wavelength.

% Ficar fotos de la lightpipe enganxada a la termopila i a la cela per referenciar

% After this first JV curve, the spectral filter guillotines move to the next dividing wavelength position, where the Keithley measures another JV curve, repeating this process at each dividing wavelength, without moving the main carriage, for each of the selected sweep types. Once the first cell measurement finishes, the carriage slowly retracts the substrate, and moves so that the next selected cell is placed on the end of the light~pipe. At this point, this entire measurement process repeats for each of the selected cells, in a completely automatic manner, until the measurement is completely finished, at which point the carriage fully retracts so that the user can safely remove the substrate without damaging the light~pipe.

% The software takes all JV curves generated during the measurement and processes them to extract all the JV parameters at every dividing wavelength. The results are then saved on multiple ``txt'' files, stored in recursive folders, with a specific hierarchical structure. This specific structure allows the software to load a given measurement, either for data visualization or post processing, while keeping the files human readable and compatible with different data processing software. Besides, similarly to (posar chapter 3) the files are structured with the author initials and measurement date, and with comprehensive folder names, so that they are easy to browse. Examples of the data and graphs resulting from a RAINBOW measurement can be seen in the following section.

\section{Rainbow Measurements}\label{ch:6 Rainbow Measurements: Rainbow Measurements}

% Example JV measurement with all the parameters plotted.

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% These dividing wavelength dependant parameters are combined to evaluate the rainbow performance of any two different cells. In this way we separate the measurement of different materials, where we can measure materials separately and then combine their efficiencies computationally. similarly to what we did in previous chapters with the EQE and JV but here we are actually measuring the real efficiency at different ilumination conditions, with the FF and the Voc instead of evaluating it from the integration of the EQE multiplied by the spectrum.

% The rainbow measurements of our solar cells resulted in this and that, for the cells that we manufactured in the previous chapter.

% The case of PM6 IO4CL does not work because it is a clear case of overshadowing where the efficiency of PM6 is not compensated by the higher Voc of the Io4cl so it is not worth it to illuminate the IO4CL as we saw in the previous calculations

% The case of Pm6 cotic works as it is a case of scavenger where the cotic works as a photon scavinger absorbing some of the photons that the Pm6 cannot absorb. That is why there is not a great increase in efficiency but there is some as we calculated before.

% We see that as expected the performance of IO4CL and COTIC is great in a tandem, in accordance to our previous calculations, with an IOBC of 34% which is great compared to the y% that we obtained in the caluculations. This is a case of highly complementing solar cells since checking their EQE curves we see they cover at more or less the same efficiency, greatly different parts of the spectrum. that is why so far this is the best combination we've found both in the calculations and in reality.

\section{Partial Deposition Techniques}\label{ch:6 Rainbow Measurements: Materials and methods: Partial Deposition Techniques}

% To bring RAINBOW solar cells to reality we need to be able to manufacture single junction solar cells by disposing them laterally in close contact with each other. To do so there exist several techniques that mainly rely on slot die (BUSCAR LITERATURA)

% Nonetheless, being a research institution rather than a technological center, we did not dispose of the means to fabricate cells by using these techniques so we had to devise a way to reproduce the same results with the techniques we had at hand. This was achieved in two of the more widespread thin layer deposition techliques in OPV: blade coating and spin coating.

% Custom blade coater working principle

% In the case of blade coating, the lateral deposition was achieved with a custom made narrow blade that constricts the meniscus to be within a certain portion of the substrate instead of allowing it to wet the entire surface. The high surface tension and viscosity of the solution prevent it from spreading through the entire substrate, resulting in a really accurate partial deposition. After several prototypes we settled on one that partially emulated the behaviour of a slot die with a central cavity that served as a reservoir for the blend solution. This reservoir stabilized the meniscus, acting as a buffer that contained the high initial amount of liquid volume, preventing the meniscus from spreading, while providing a constant supply of liquid along the deposition process, preventing the meniscus from disappearing. As you can see in figure x, the results are really precise and repeatable for a wide variety of blend compositions.

% Custom blade coater real and rendered images +

% The blade design was fully designed and 3D printed by us, using a UV curable resin 3D printer that provided the high accuracy needed for the small slot die features, as well as high solvent resistance thanks to it's high crosslinkage ratio.

% For the case of spin coating, to our knowledge, there are no reported techniques that are capable of a conformal partial substrate deposition. The technique that was closer to what we needed consisted on masking half of the substrate with PDMS and depositing the solution on the other half before spinning it. The close contact between the PDMS and the glass kept the solution away from that part, resulting in a partial substrate deposition. The main problem with this technique was that the lateral PDMS-solution interface induced an additional meniscous that resulted in huge coffee stains, with wide thickness variations within the active layer (figura ?).

% (Figure where there is a spin coater with half the substrate with a solution and then we spin it and the solution moves only outwards, and example with four maybe)

% Since the meniscous was the problem we tried to eliminate it by preventing the solution from contacting the PDMS. To do so we carefully deposited the solution on the substrate, leaving a small gap between the liquid and the PDMS. The resulting active layers were perfectly homogeneous without major thickness variations. Upon further considering what had just happened, we realized that the PDMS was completely unnecessary, that is because as we see in figure x, the centrifugal forces acting upon the liquid will always push it outwards, never to the other side. Experimenting with this hypothesis we confirmed that by depositing the solution in only one half of the substrate, and regulating the amount of liquid, maximum angular velocity and acceleration, we could reliably cover half of the substrate, leaving the other half completely untainted (figure x). At least in theory, this new technique allowed us to partially cover any substrate with n different layers, as long as their distribution is radial, since the main force the liquid experiences is radially pointing outwards, forcing the liquid away from the center (Figure). Consequently, we named this technique Partial Coverage Radial Spin Coating (PCR) Spin Coating.

% Picture with examples of half deposited spin coated substrates, and if you can a 4 part substrate.

% One disadvantage of this technique are that if we do not adjust the amount of liquid, the angular velocity and acceleration, the solution can be dragged through the substrate, staining the uncovered part. However, by tuning the parameters it is not difficult to achieve optimal deposition conditions. The other main disadvantage is that the precision of the partial coverage greatly depends on the steady hand of the operator during the deposition. To mitigate that we have 3D printed a small guide that guarantees a straight line every time, as we can see in figure x.

% Picture of the small guide during the deposition process.

\subsection{Proof of concept device}\label{ch:6 Rainbow Measurements: Rainbow Measurements :Proof of concept device}

%Picture of the device

% Graphs with the JV curve measurements and

% miquel graph with spectral measurements and table with the performance. For the two rainbows that work.

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% With the partial deposition techniques we manufactured a proof of concept device that looks like the one in figure x and it works like a charm, but that is not yet true.

% We see the results in this graph where we get an x% IOBC but we were not able to reproduce the efficiencies obtained in hasselt for the IO4CL so we coulb not manufacture a working device using that material but the PM6Y6 cotic works okay I guess.

\section{Conclusions}\label{ch:6 Rainbow Measurements: Conclusions}

% In this chapter we have manufactured an expermiental setup, capable of characterizing RAINBOW solar cells, which we named SOLS. This setup is capable of carving an input spectrum into any desired shape by selectively modulating the intensity at each given wavelength. To do so it takes light from any light source as an input and separates it into its spectral components. This lateraly spread lightbeam is then spacially filtered, before being refocused into a light mixer that outputs a fully homogeneous spot.

% We have demonstrated that, as long as the desired output power does not exceed the input power in any wavelength, and accounting for the losses, this setup can produce a wide range of custom shaped spectra. Besides, this spectral shaping can be dynamically controlled with two motorized guillotines that allow us to emulate the conditions from previous chapter's simulations.

% To perform the RAINBOW measurements we utilized the SOLS setup to divide the solar spectrum in two parts at a certain dividing wavelength, illuminating the cell to be measured with one of the parts while measuring its performance at each dividing wavelength. These measurements provide partial efficiency data, as well as individual JV curves at each dividing wavelength with all their associated JV parameters, which can be later combined to evaluate the RAINBOW tandem performance of a particular cell combination.

% In order to manage all the data and control all the instruments necessary to perform RAINBOW measurements we have developed a powerful piece of software, and an automated XYZ stage that when combined are capable of conducting all the operations needed during the experiments while at the same time providing an intuitive graphical user interface and a comfortable user experience.

% The first cell measurements of the SOLS setup were performed with homogeneous cells manufactured in the previous chapter, in order to evaluate their real RAINBOW combined efficiency. These measurements gave great results, with IoBC of x% for PM6:IO-4Cl with PTB7-Th:COTIC, and y% for PM6:Y6 combined with PTB7-Th:COTIC, further confirming the calculations performed in the previous chapter.

% To fabricate a proof of concept rainbow device, we developed different partial coverage deposition techniques based on blade coating and spin coating. In the case of blade coating we took advantage of the blend solution surface tension and viscosity to control the meniscous with a custom 3D printed blade that allowed us to partially cover a substrate in a highly controlled and repeatable way.

% On the other hand, PCR spin coating achieves partial subsrate coverage by making use of the centrifugal forces present during the deposition. By carefully depositing the solution in a radially simetrical way, only covering a fraction of the substrate before spinning it, and controlling the angular velocity and acceleration, the centrifugal forces present during the process force the liquid outwards leaving the uncovered portion untainted. In this way, we can accurately deposit a homogeneous layer on a small section of the substrate, resulting in a very promising deposition technique.

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% With these deposition techniques we manufactured a proof of concept device that works nicely The combinations using IO4Cl did not work because we had not mastered the deposition conditions of this material in ICMAB, but the deposition of the two other materials work wonderfully in proof of concept devices that perform with an IOBC of x%.

%% Appendix

\subsection{Concave mirror}\label{ch:6 Rainbow Measurements: Appendix: Concave mirror}

% To reconcentrate the light coming out of the Amici prism into a small spot, being only laterally dispersed, we required an optical element that provides lateral concentration, such as a cylindrical lens or mirror. The main problem was that, since the spectrum is filtered by spatially blocking it, the filtering wavelength resolution was directly proportional to the width of the spectrally spread beam.

% The first step to determine which reconcentrating solution to use was to measure light divergence after the Amici prism. To do so we used a simple ray tracing approach, where, by placing a screen and a beam blocker at an exact distance, and moving the blocker at precise distance intervals while measuring the changes on the screen, we could triangulate the approximate divergence of the beam at each position. (figure x) With these results and cad software we designed the needed curvature to reconcentrate the divergent beam into one small spot (figure x right).

% microfigura de triangulació I foto de com vas fer la triangulació

These measurements revealed that the light beam would be really wide after all the colours are properly separated. The main problem with that is that a widespread beam can only be reconcentrated by using a lens or mirror as wide as the beam itself, in order to collect the all the light. Besides, colour dispersion is not constant for every wavelength, with higher dispersion for shorter wavelengths, so the curvature of the reconcentrating lens or the mirror is not necessairly spherical.

In order to reconcentrate this light beam, it was clear that we were going to need a big, custom solution. However, big cylindrical lenses are not usually commercially available, let alone big custom curvature ones, and they can introduce further dispersion into the system with chromatic aberrations, tipping the scale towards the mirror solution.

Similarly to the lenses, such a wide custom mirror is not easy to find commercially unless custom made However, since we did not have accurate manufacturing dimensions, and this first mirror was just for prototyping purposes, we discarded the commercial route. That left us with just one possible course of action, manufacturing the big custom mirror ourselves, with our beloved technique, 3D printing.

% The first approach consisted on directly polishing the 3D print itself to achieve a mirror finish, to be covered with silver via thermal evaporation, providing great reflection capabilities. Even though the results are not that far from an ideal mirror (figure x), achieving a perfect mirror finish polishing by hand proved to be more challenging than expected. As another alternative, we tried coating the 3D printed surface with epoxy and paint to smooth out the layer lines and defects. However, even with the mirror finish that such paints provide, irregularities on the macro scale resulted in poor focusing capabilities.

%Foto del mirall hand polished

The definitive solution came when we tried to use mirror finished PETG 0.5~mm thick sheets, which we clamped onto the custom curvature piece with a 3D printed adapter. The PETG sheet completely conformed to the custom curvature when bolting it to the 3D printed piece. This entire assembly was placed in the thermal evaporator, and a layer of Ag followed by a layer of LiF were deposited. The thick layer of Ag was the main reflective layer, acting as a first surface mirror, while the thin layer of LiF provided corrosion resistance to the Ag layer without significantly affecting the spectrum. This type of coatings are commonly used in the industry for corrosion protection in first surface mirrors (Citar Thorlabs). The main advantage of using a thin inexpensive PETG sheet is that, if anything happens to the mirror, we just need to replace the sheet and reevaporate, without having to 3D print the custom curvature mirror backing again.

Foto del mirall obert i printed I amb tapa també

% Because of the inherent error during the previous divergence measurement, the mirror focus was not a perfectly narrow line, but rather a 7~mm wide strip. However, since the beam required further colour remixing to correct for directionality inhomogeneities the spot size was not a significant limitation.

% As an additional bonus, we added a lid to the mirror so that it is protected from debree and accidental contact. Being a first surface mirror, it is incredibly sensitive to scratching and finger grease.

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% Ficar fotos del mirror i també renders si vols, un render de com enfoca la llum ho petaria molt!!!

\subsection{Light Pipe}\label{ch:6 Rainbow Measurements: Appendix: Concave mirror}

% After reconcentrating the light beam with the mirror, we obtained a seemingly homogeneous white narrow spot. However, further characterization revealed significant spectral homogeneity problems in the focal point, arising from the previous colour separation. These inhomogeneities were made apparent when, by spectrally filtering the incoming beam, the spot shape was completely distorted, narrowing proportionally to the filtered fraction.

% Picture of the spot and half the spot

% This posed a serious problem, since most cells operate best under homogeneous lighting conditions. Having half of the cell in the dark during a measurement can severely hinder its performance, compromising the accuracy of our measurements. That is why we endlessly tried different diffuser and lens combinations to homogenize the beam, all of which resulted in heavy light loss, combined with intensity inhomogeneities, forcing us to discard them.

% An unconventional idea that we thought might just work was to use a mirror tube with 5 edges that, if long enough, would randomize the direction of each colour component. The working principle of this hypothesis, as can be seen in figure x, is that a small difference in incidence angle will result in a complete different optical path. To test the concept, we hand crafted a very crude version (figure y) that produced mesmerizing results with really high spectral homogeneity, especially considering the dodginess of the contraption (figure x).

% Figura del concept amb un tubo en fusión i 5 rajos entrant paralels i sortint com els hi toqui sortir

% ficar figure del tubo de miralls i les formes que generava

% Knowing this was a viable solution, we scoured the web for optical suppliers that would provide a similar commercial alternative. To our surprise, we found an even better solution called a light pipe, a glass rod that has been faceted with either four or six faces, which takes advantage of total internal reflection to homogenize light, while at the same time directing it, similarly to an optic fiber. The light pipe working principle is really similar to that of the mirror tube, with significantly lower losses in each reflection. On top of that, light pipes made from fused silica, which barely absorbs in the UV range, can be used in future SOLS setup embodiments, with extended input wavelength ranges.

% The only disadvantage of using a light~pipe was that, being a long narrow glass tube, it is really susceptible to fracturing with any accidental tool drop or an erroneous XYZ stage movement. To mitigate such risk, we secured the light~pipe with a complient 3D printed fixture that can accommodate a certain degree of deflexion, returning to its original position after the force is removed. This complient fixture, figure x, was fully 3D printed using a combination of flexible and rigid filament, with a specific shape that allows for some deflexion on the xz plane, and greater deflexion on the y direction. The y direction has the lowest resistance deflexion to make sure that when the cells and the light~pipe come into contact, the forces on both elements are minimal. Besides, variations in the y position do not result in a significant change in the measurements, while variations in the xz position do.

% Figure rendered lightpipe holder, if you can with colour mixing

% The light~pipe on its own provided great light homogenization (figure x), however colours still had some amount of directionality. To reduce this direccionality and provide the most accurate possible measurements, we added a diffuser in front of the light~pipe that spread light much more evenly, resulting in a completely white spot even away from the lightpipe. Curiously, when we move further away from the pipeline, its hexagonal pattern is made apparent, resulting in an image that resembles a graphene lattice.

% Figure light homogenation with and without dispersive element