Inkjet Printing of Swathe-Free Displays

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Abstract

Visible swathes are an unwanted artefact of the inkjet printing process used in the production process for displays, and the reduction or elimination of swathes is crucial to producing displays of high quality. Causes of swathing such as physical swathes due to dried film asymmetry at swathe joins and drop volume variability have been identified and are described.

As a result significant developments have been made in these areas. New ink formulations have significantly reduced the occurrence of physical swathe joins caused during the drying of inks, and print process and strategy, for example through the use of interlacing, have enabled very high quality displays to be produced with the inkjet printing process at CDT.

Background

Solution processing of Organic Light Emitting Diode (OLED) materials, in particular Polymer OLED (P-OLED), to fabricate displays offers several advantages over the alternatives such as scalability to large substrates and lower costs, and inkjet printing is established as a very flexible method for depositing the liquids used. However, the inkjet printing process generally requires the printhead(s) to be passed many times over the substrate in a series of swathes to cover the entire substrate area. Where multiple swathes occur in a printed display it is common to be able to observe repeating variations in the emission from the display, attributable to the swathes, which are visible (for example visible stripes) and therefore undesirable.

Such visual effects are also common in conventional graphic printing. Small errors in drop placement resulting from errors in the stepping of the head or substrate can result in very visible stripes at the swathe joins. However, in the printing of displays where the pixel patterns are pre-defined with physical and/or surface energy patterning, the pixel locations cannot become offset in the same way that dots in a graphic image can, and so other mechanisms are responsible for visible swathe errors.

Experimental

Displays were printed with a number of Litrex 140/142 printers at CDT's Technology Development Centre in Godmanchester, UK. Firstly the Hole Injection Layer (HIL) is printed onto the prepared display backplane, and this is dried and baked. Then an interlayer is printed, dried and baked before the Light Emitting Polymer (LEP) layer is printed, dried and baked. The printed substrates then have a cathode deposited before the displays are encapsulated, scribed and broken down into individual displays and then tested.

The thickness profiles of baked films were measured on substrates after the inkjet, drying and baking processes (i.e. without cathode or encapsulation) using a white light interferometer supplied by Zygo. The interferometer measures the film thickness profile along both axes of the patterned pixels (length and width) relative to unprinted reference areas patterned around the pixels. The interferometer was also used to measure the volume of drops printed onto plain glass by measuring the area and profile of the cap formed.

As well as visual assessment of illuminated display uniformity with the naked eye, the emission profile of displays, regions of displays and individual pixels was quantitatively measured using a Prometric camera rig. This provides luminance data enabling any swathe effects to be quantified as well as showing intra-pixel variations.

Physical swathes

An example of pixels in a display clearly showing a visible swathe join is shown in figure 1.

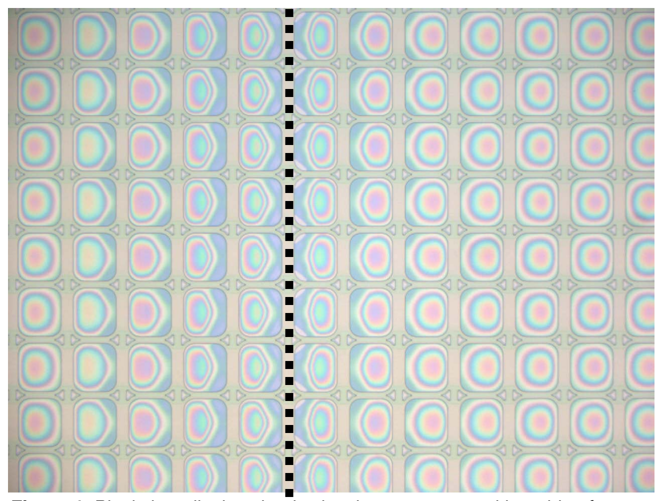

***Figure 1**. Pixels in a display clearly showing asymmetry either side of a swathe join (dashed line).*

Interferometer profiles from pixels either side of a swathe join (figure 2) show that the usual symmetry of the thickness profile across the width of the pixels becomes asymmetric close to the swathe join. Film thickness has been reduced at the pixel edge closest to the join and increased at the edge away from it.

The shape of the profiles of dried and baked films is principally determined by the way in which the wet, as-printed film dries. Once solvents have evaporated to a gel point, material transport ceases and the shape of the final profile is determined by the profile at that time. Hence it is inferred that the asymmetric profiles are a result of asymmetric drying conditions at the edges of printed swathes.

Once the whole display has been printed, the swathe joins within the display should see uniform drying conditions having printed pixels on both sides, but immediately after any given swathe is printed part way through the printing of a display, this may not be the case. If rapid evaporation occurs, a solvent-rich atmosphere occurs over the printed region, but much less so beyond the swathe edge. Since the solvent atmosphere affects the rate of drying through the establishment of an equilibrium, the swathe edge can be expected to dry quicker than the bulk resulting in material transport away from the edge and the profile thinning observed there.

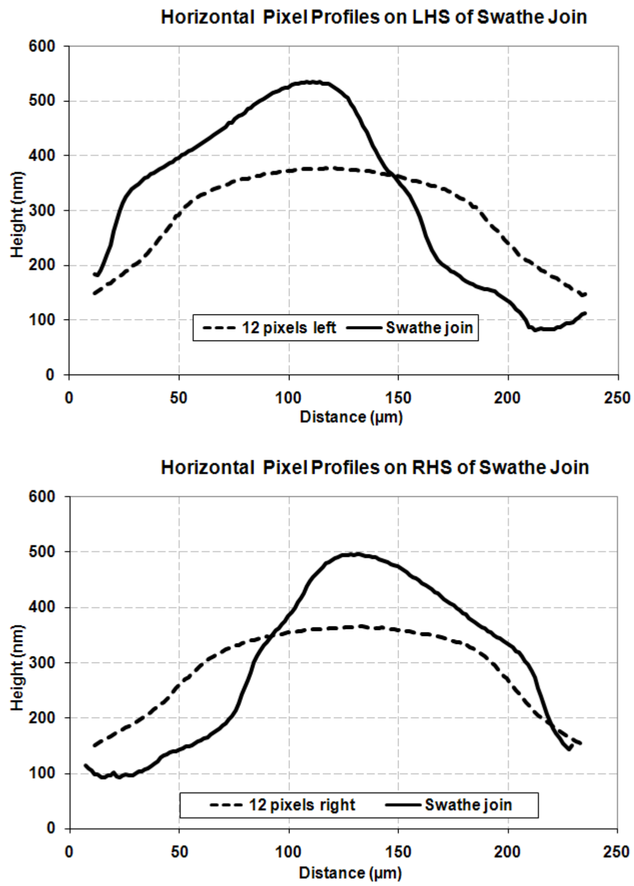

Figure 2*. Showing the asymmetric film thickness profiles at swathe edges (solid lines) on the left (top) and right (bottom) of the swathe join compared to pixels further away from the join (dashed lines).*

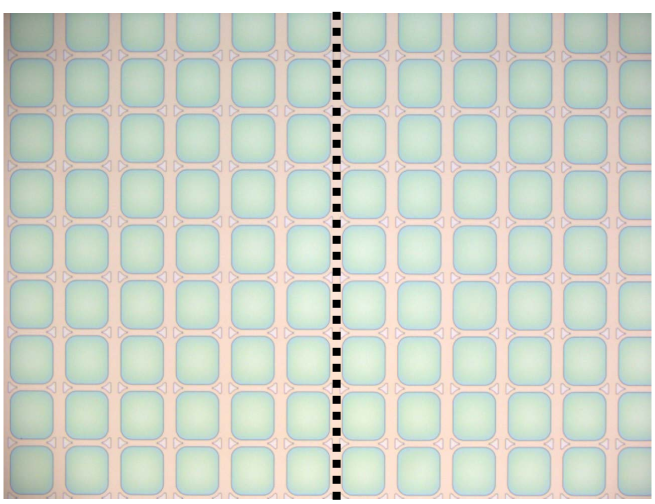

Figure 3*. Pixels printed with a reformulated ink show no visual change across the swathe join (marked as dashed line).*

A solution to this is to prevent the printed swathe drying in this immediate, uncontrolled manner. Reformulation of the inks used virtually eliminates any drying at the ambient conditions used for printing and allows for a controlled drying step after printing to be used. This not only gives uniform drying conditions across the majority of the printed area (note that edges will still see a vapour pressure gradient), but allows the final film profile to be optimised by controlling the conditions of the drying step.

Figure 3 shows the effect of such an ink reformulation on the printed pixels. The interferometer results in figure 4 show that the asymmetry in dried film profiles at swathe joins has been eliminated, and a flatter film has also been achieved. Through further reformulation and process development, film flatness has been improved still further.

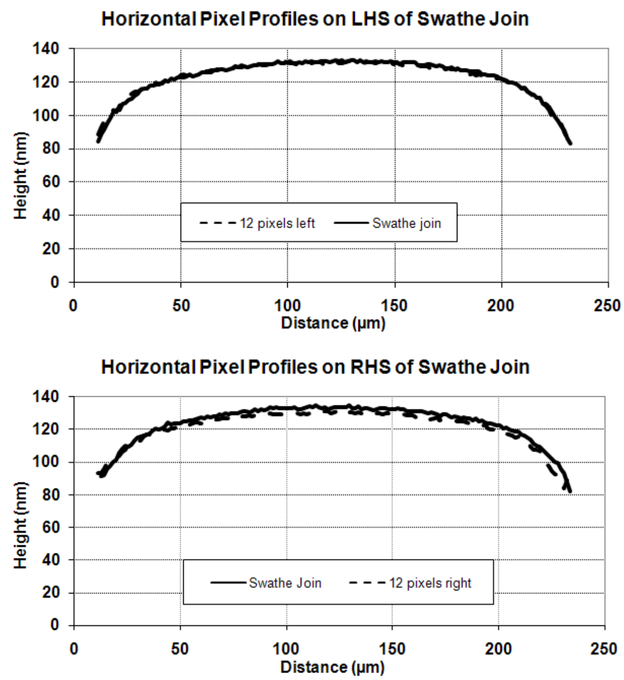

Figure 4*. Showing the symmetric film thickness profiles both at swathe edges (solid lines) on the left (top) and right (bottom) of the swathe join and in pixels further away from the join (dashed lines).*

Drop volume variability

The cause of a display showing variable emission which repeats at the swathe pitch may not in fact lie at the join between swathes, or if it does, may not be due to any fundamental difference in behaviour there. The drop volume produced by each nozzle used in printing the swathes was measured by printing drops onto plain glass and measuring their volume with the interferometer. The resulting profile of drop volumes across the swathe was then compared to the profile of pixel emission and this is shown in figure 5.

The drop volume profile has been inverted as reduced volume produces a reduced film thickness in the pixel which in turn produces higher emission. The drop volume and emission profiles then show good agreement suggesting that drop volume variation is responsible for variations in the emission profile across a swathe. If this profile contains rapid short range variation, it can become easily visible, and when repeated with each swathe appears as a swathe defect.

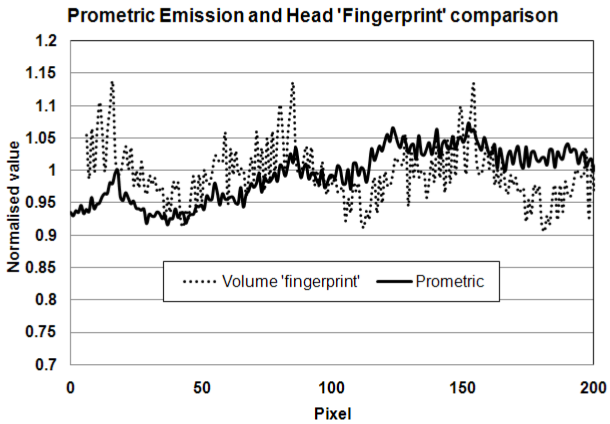

Figure 5. *Showing the comparison of Prometric camera emission data (solid line) with the adjusted drop volume profile 'fingerprint' (dashed line) – key features of the two curves are coincident.*

Alternatively, the variation within a swathe may be smooth and subtle enough to not be visible in isolation, but may give rise to a significant end-to-end difference. When multiple swathes are then printed, this difference gives a sharp discontinuity in the emission profile at swathe joins which is highly visible.

Through a process developed at CDT, the drop volume profile has been flattened to significantly reduce both local variations and end-to-end differences in a swathe. An example of a flattened drop volume profile is shown in figure 6 and the resulting improvement in the emission profile is shown in figure 7.

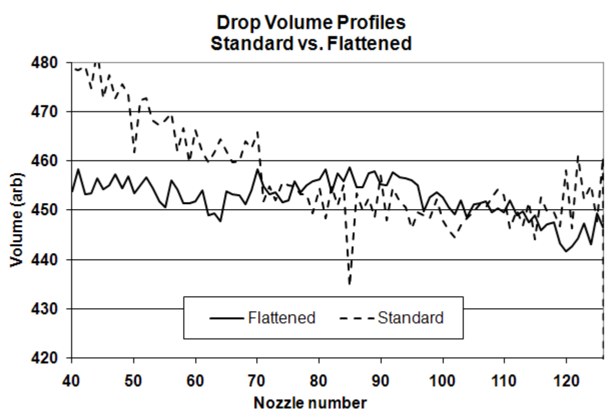

Figure 6. *Showing the much flatter drop volume profile across the range of printing nozzles after the flattening process compared to standard.*

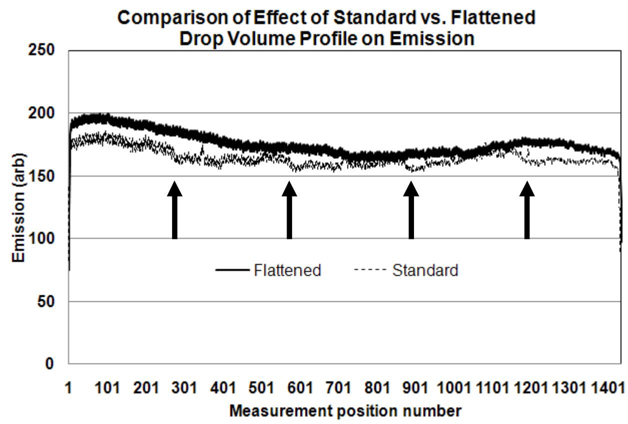

Figure 7. *Showing the improvement given by drop volume profile flattening (solid line) compared to standard (dashed line). Four features (marked with arrows) can be seen on the standard curve corresponding to end-to-end difference in the joins between the five swathes. Note the longer range variation underlying both curves due to other effects.*

Interlacing

Whether it is due to asymmetric profiles from drying effects, due to drop volume variations, or due to other effects, a key factor in the visibility of swathe effects is the production of a continuous feature along the length of a swathe when conventionally printed. When printed in this way, a single nozzle prints every pixel in a column on the display, and this renders any defect highly visible.

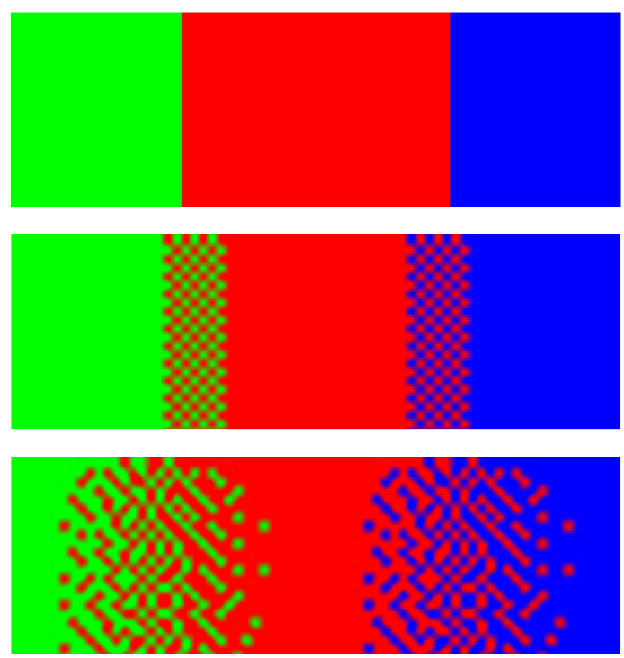

Figure 8. *Showing standard printing (top) with 3 swathes represented. In the centre a simple overlap pattern with small overlap distance is shown while the bottom diagram illustrates a randomised pattern over an even greater overlap distance.*

Interlacing is a process well established in graphics printing whereby passes of the printhead are overlapped allowing two or more different nozzles to be used to print any given column in the array. There are countless alternative schemes varying the amount of overlap, the number of passes and the patterns of drops printed on each pass, but a number of alternatives have been tested at CDT and their effect on apparent display uniformity assessed, examples of which are shown in figure 8.

'Simple' interlacing where the printed pattern in the overlapped region has a simple structured pattern gave a noticeable improvement over non-interlaced displays, but more randomised interlacing patterns gave further improvement.

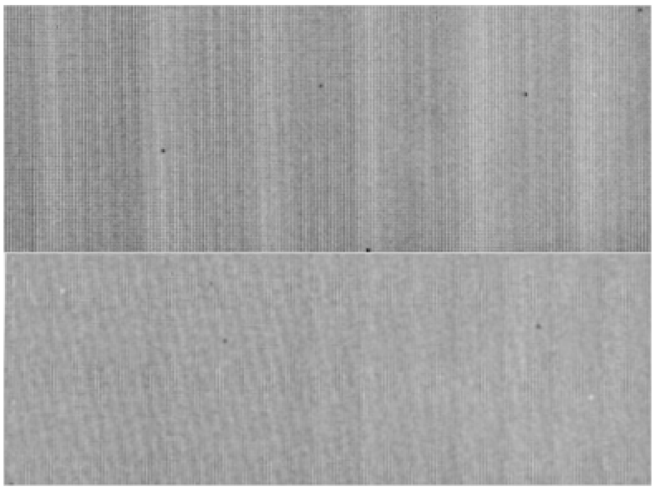

***Figure 9**. Showing the benefit of interlacing (bottom) compared with the non-interlaced display region (top), which has swathes clearly visible.*

Figure 9 shows areas of displays printed with and without interlacing and in figure 10 the associated emission profiles across the displays. Both the visual appearance and the quantified emission profile show a significant improvement when interlacing was used.

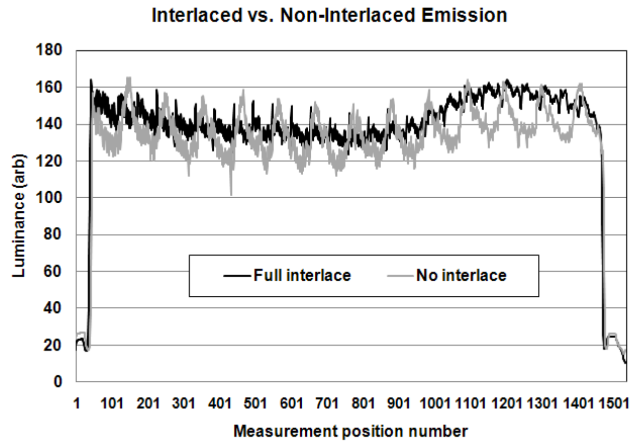

***Figure 10**. Showing the emission profiles of both the interlaced (black curve) and non-interlaced (grey curve) displays. The pattern of swathes is clearly visible in the non-interlaced case while the interlaced display exhibits lower amplitude, higher frequency variation. Note the long range underlying variation from other causes in both cases.*

Conclusions

Several causes of visible swathes in inkjet printed P-OLED displays have been identified including physical swathe joins and drop volume variations, and methods to combat them have been developed. In addition, an interlaced printing method has been developed which significantly reduces the effect of any residual swathe-wise variability on the visual appearance of displays. Combining these methods has allowed the printing of displays with display uniformity well within commercially acceptable limits.

Author Biography

Mark Crankshaw received his B.A. in Natural Sciences from the University of Cambridge (1995) and his Ph.D. in Materials Science from the University of Cambridge (2000). After 7 years at Xaar as a Development Engineer and later Technology Specialist working on actuator development he joined CDT in 2007as Principal Engineer in the Process Engineering group. He is a member of the IOP and IOM3