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A new PDAF correction method of CMOS image sensor with Nonacell and Super PD to improve image quality in binning mode

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Abstract

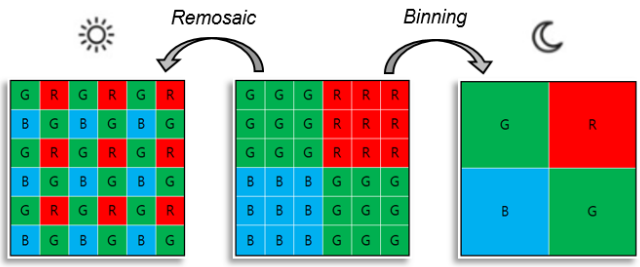
This paper presents a new PDAF correction method to improve the binning mode image quality in the world's first 0.8um 108 mega pixel CMOS Image Sensor with Samsung Nonacell and Super PD technology. PDAF pixels had been fixed by bad-pixel-correction (BPC), referring to the adjacent non-PDAF pixels in the conventional correction method. We demonstrated a new method, named Dilution mode which output their own seed value within the 3x3 same color-channel pixels to video images and deliver AF information through the separate embedded data. As a result, the PDAF artifact, such as a false color, broken line and dot artifact in a high frequency pattern and overall image detail have dramatically improved in dilution mode.

Introduction

High resolution-image sensor and multi-camera have become the latest trend in smartphone market. In addition, demand for high performance CMOS image sensor, such as low noise characteristics, wide dynamic range, fast readout speed and ultrahigh resolution is increasing. Meanwhile, pixel scaling is continuously going deeper into sub-micron pixel. As pixel scaled down, overall pixel performance has been degraded, such as sensitivity, full-well capacity (FWC) and signal-to-noise ratio (SNR) due to the smaller area to accept incident light and implement photodiode (PD) [1]. Recently, a 0.8um pixel pitch and 108Mp resolution CMOS image sensor have unveiled for mobile application thanks to Samsung ISOCELL technology, including buried PD and vertical transfer gate (VTG), as well as full depth of deep-trench-isolation (DTI) structure. It contributes to secure higher FWC in smaller PD area and eliminate electrical crosstalk. Moreover, the sensitivity and optical crosstalk have improved by Samsung ISOCELL Plus technology, applying low refractive index material to grid structure inside of each color filter (CF) [2].

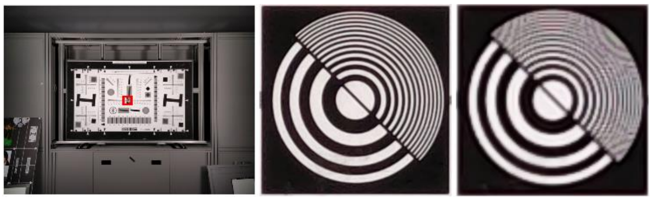
Nonacell consists of 3x3 pixels in same color channel as shown in **Figure 1**. In a high illuminance condition, each individual pixel is reconfigured in Bayer pattern without resolution reduction by the embedded Remosaic function. Remosaic mode is normally applicable to a capture scenario for ultrahigh resolution picture and provide definitely clear image as shown in **Figure 2**. In a low illuminance condition, nine pixels, forming the same 3x3 color channel are combined into one pseudo cell by using a Nona binning mode. The binning mode is generally used for a preview and movie scenario due to the advantage of high sensitivity and frame rate.

Image sensor provides PDAF information to support a fast Auto-focus in camera system. There are several pixel structure for PDAF, such as a metal shield AF and Super PD as shown in Table 1. The metal shield AF is the most traditional PDAF structure and it requires additional fabrication process for white CF and gives poor AF sensitivity because of the metal shield. On the other hands, Super PD has the advantage of simple fabrication and high AF sensitivity. Recently, Super PD is the most widely adopted AF structure in sub-micron pixel CMOS image sensors.



(a) Remosaic mode (b) Nonacell pattern (c) Nona-binning mode

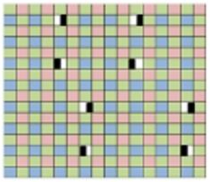
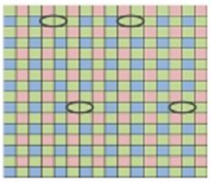
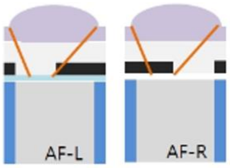
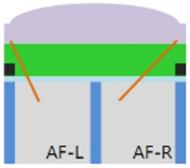
Figure 1. Nonacell pattern and embedded Remosaic function



Sample Picture (a) (b)

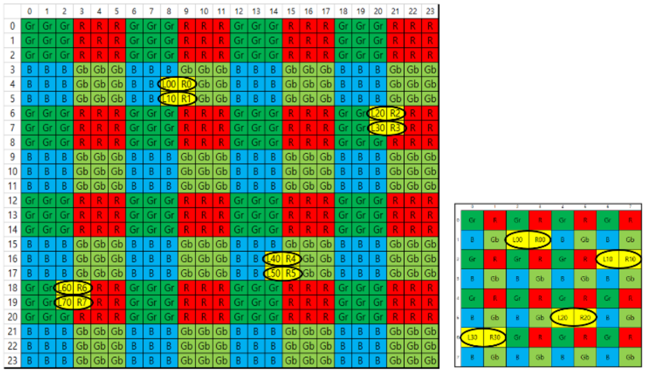
Figure 2. Resolution Chart image of (a) 108Mp Remosaic mode, (b) 12Mp Nona-binning mode

Table 1. PDAF Structure in CMOS Image Sensor

	Metal Shield PDAF	Super PD
Top View		
Cross-sectional View		

Sensor Architecture

Figure 3. shows the PDAF pattern of Nonacell CMOS image sensor in this work. In Remosaic mode, the PDAF density is 1/36 and the pattern consists of 2 pair of super PD. They are placed across the different color channels. The PDAF density have been increased up to 1/8 in Nona-binning mode. The higher AF density improve AF accuracy and reliability, but causes side-effect, image quality degradation. Image quality and PDAF performance determined by AF pixel density are normally trade-off.

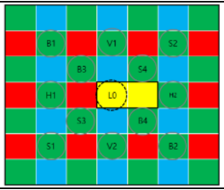
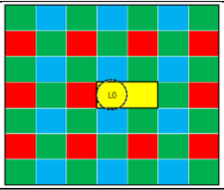


(a) (b)

Figure 3. PDAF pattern of (a) 108Mp Remosaic mode, (b) 12Mp binning mode

The conventional PDAF correction method is based on bad-pixel-correction (BPC), replacing AF pixel to adjacent normal pixels. Recently, in order to suppress AF artifact, sensor provide an advanced algorithm that detect the directionality of the image pattern near the PDAF pixel area, and determine which area to be referred for the correction. For example, when the algorithm detects no directionality in the pattern, the PDAF pixel will be replaced by referring to all of the same color-pixels within the kernel of 7x7 or 9x9 pixels. If Slash pattern is detected, PDAF correction will refer to the pixels which are located in only slash direction as shown in Table 2. In spite of the advanced algorithm, the AF artifact still occur because of a higher AF density, directional misrecognition or exceptional case of direction. In order to overcome the limitation of conventional method, new correction method, named Dilution mode have been introduced. In Dilution mode, a Nonacell, which contains AF pixels, outputs its own seed value to a binning output and deliver AF information by embedded data, which is a PDAF Tail mode.

Table 2. Comparison of PDAF Correction Algorithm

	Conventional Correction Method	Dilution Mode
Color Filter Pattern		
Flat pattern	L0 = average of all adjacent pixels	L0 = seed value from own Nonacell
Vertical pattern	L0 = average of V1,V2	
Horizontal Pattern	L0 = average of H1,H2	
Slash pattern	L0 = average of S1,S2,S3,S4	
Bash pattern	L0 = average of B1,B2,B3,B4	

Recently, the image sensor with PDAF pixels typically support PDAF Tail mode. The sensor provides a clean image from AF pixels by internal BPC process and AF information through the separate embedded data. **Figure 4**. Shows a simple block diagram of PDAF correction and Tail mode output process. (a) In the data from the pixel, raw PDAF pixels are interlaced in the video image. (b) The processed PDAF are interlaced in a video image by FE-ISP block and the image is sent to PDAF buffer and BPC block in parallel. (c) In BPC block, AF pixels are corrected by conventional correction method. After the process, the video image is clean from PDAF. (d) PDAF buffer collect only PDAF data, then transfer to PDAF output buffer. The fixed image from Video Output Buffer and collected PDAF data from PDAF Output Buffer are combined in Arbiter. (e) Finally, the fixed video image and PDAF information are transmitted in an interleaved way by different data type or different virtual channel.

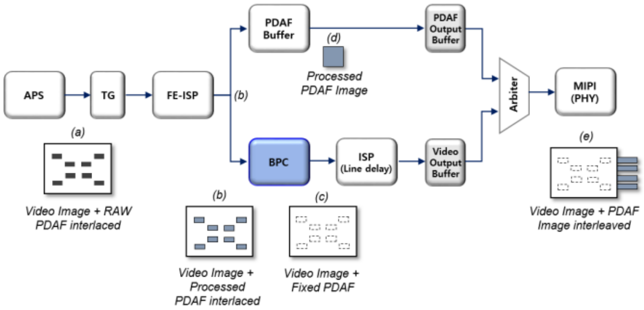
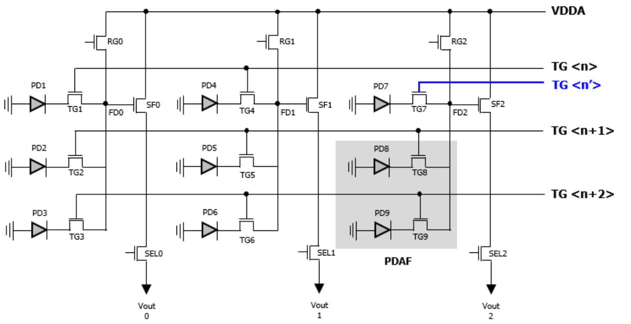
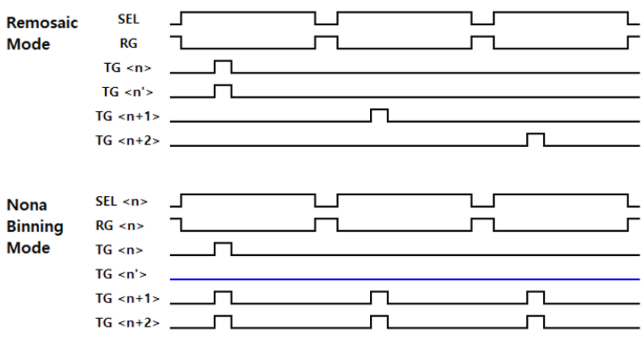


Figure 4. Block Diagram of PDAF correction and Tail mode output

Figure 5. is showing the schematic diagram and pixel operating timing for Remosaic and Nona-binning mode. Three PDs in vertical direction share one Floating Diffusion (FD) and These three 1x3 shared pixel units are combined to create 3x3 Nonacell pattern. In Remosaic mode, each row operates in sequential order and gives individual output. In Nona binning mode, 9 pixels are read simultaneously so, signal electron accumulated in each 1x3 Photo diode are summed in shared FD. And the three vertical directional output are averaged in voltage domain. In case of 1x3 pixel unit containing PDAF, shown in **Figure 5 (a)**, PD7 is a normal pixel, whereas PD8 and 9 are PDAF pixel. Because these three PDs share one FD, PD7 output may distort AF information if normally operate in Nona-binning mode. PD7 should normally operates in Remosaic mode, but discarded in Nona-binning mode. Therefore, we allocated



(a)

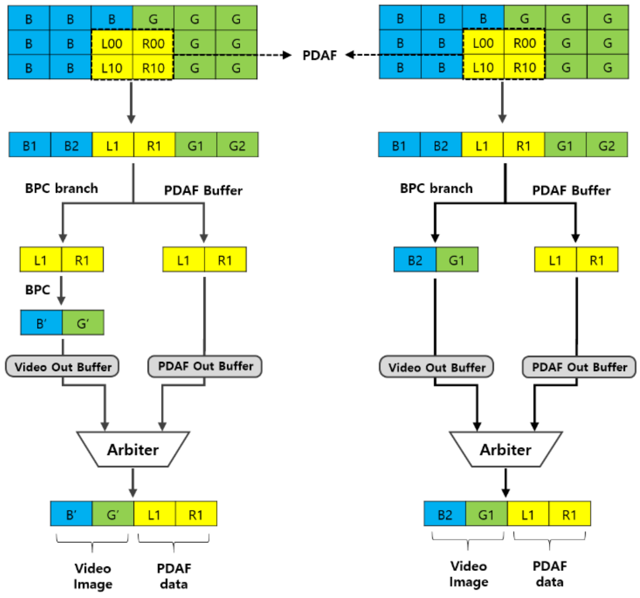


(b)

Figure 5. (a) Schematic diagram of Nonacell, containing PDAF pixels, (b) Pixel operating timing diagram of Remosaic and Nona-binning mode

an additional TG control line for PD7. TG n' which control TG7 normally operate in Remosaic mode but, always stay low in Nona-binning mode to discard PD7 signal.

Nona-binning mode in this work provides 3 vertical charge summation plus 3 horizontal voltage average as shown the example in **Figure 6**. After the three vertical charge summation, pixel output gives 6x1 data from 2 pair of Nocacell. Among them, B1, B2, G1, G2 are from normal pixel whereas L1, R1 from PDAF. These 6x1 data are delivered to both BPC and PDAF buffer in parallel. In conventional correction method, the correction operation is performed in BPC branch by referring to the neighboring pixels, then deliver the replaced value (B' and G') to Video Output Buffer. On the other hands, B2 and G1 data, the original seed value of each Nonacell are delivered to video output buffer instead of BPC process in Dilution mode. Therefore, there are few AF artifacts and no phase error even in high frequency pattern images because the binning output value was obtained from its own Nonacell and chosen by the center of the mass.



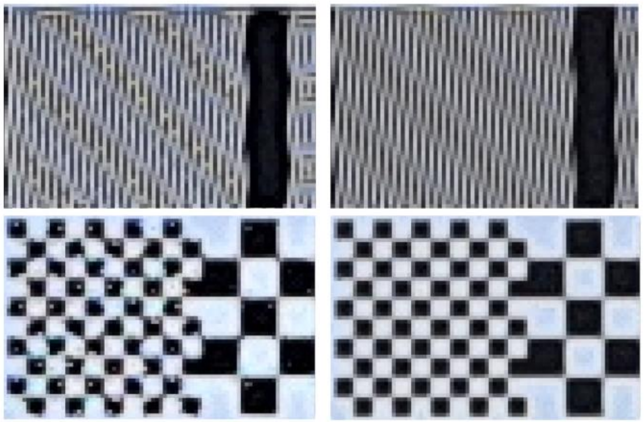
(a) *(b)*

Figure 6. Nona-binning process for (a) Conventional correction method, (b) Dilution mode

Experimental Result

Figure 7. shows the 12Mp Nona-binning mode image of conventional correction method and new dilution mode. The AF artifact such as a broken line, false color and dot artifact in high frequency pattern have dramatically improved and much clear image is provided in Dilution mode.

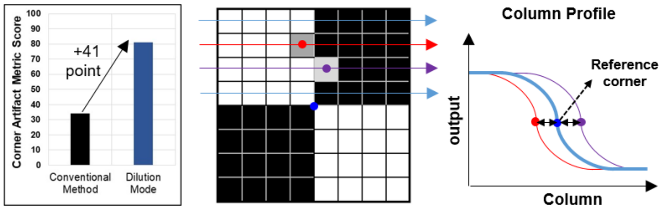
Sample Picture



(a) *(b)*

Figure 7. Captured image comparison of ISO resolution chart by using (a) Conventional correction method, (b) Dilution mode

The conventional method and Dilution mode scored 34 and 81 point in Corner Artifact Metric, respectively (**Figure 8**). It means that the dot artifact has improved considerably in Dilution mode, as seen in sample images. The test metric is one of the evaluation tools which numerically measure the dot artifact. The tool detects the position of the corner in the chessboard shaped grid pattern, extract a line profile for each row and column, and insert the profile into a sigmoid function to find the center point. The dot artifact can be quantified by measuring the distance between the reference corner and the center of the line profiles. The shorter the distance, the larger the score.

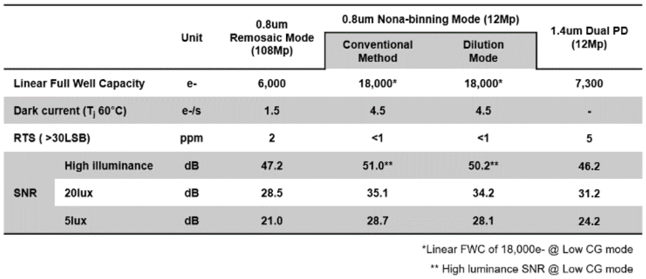


(a) *(b)* *(c)*

Figure 8. (a) Corner Artifact Metric Score of conventional correction method and Dilution mode (b) Sample of dot artifact (c) Column Profile of dot artifact sample for Corner Artifact Metric calculation

Table 3. shows the evaluation result of Remosaic and Nona-binning mode. Since Nona-binning mode provides three charge summation, is giving three times larger result in linear FWC and dark current compared to Remosaic mode. We have achieved linear FWC of 18,000e- in Nona-binning mode by using dual conversion gain (DCG) technology. Previously, the limitation of the FD dynamic range (DR) had constraint on FWC gain but, DCG technology in our work presented a solution for the issue [1]. The conventional correction method and Dilution mode is equal in FWC, dark current and random-telegraph-signal (RTS). In 12Mp Dilution mode, SNR slightly degraded compared to conventional method. It is mainly due to the difference in correction method. Because the binning output of Nonacell containing PDAF is an averaged value of the adjacent pixels, the noise of PDAF pixels attenuates in conventional method. Whereas Dilution mode gives its own seed value, which is not averaged. Despite of slight SNR degradation, Dilution mode is still superior to 12Mp output mode of 1.4um sensor by 3 to 4dB. Thanks to an overwhelming resolution, the CMOS image sensor in this work support 12Mp output in 3x3 binning. It is an obvious advantage of ultrahigh resolution and Nona-binning mode.

Table 3. Comparison of Evaluation Result



		Unit	0.8um Remosaic Mode (108Mp)	0.8um Nona-binning Mode (12Mp)		1.4um Dual PD (12Mp)
				Conventional Method	Dilution Mode	
Linear Full Well Capacity		e-	6,000	18,000*	18,000*	7,300
Dark current (T_j 60°C)		e-/s	1.5	4.5	4.5	-
RTS (>30LSB)		ppm	2	<1	<1	5
SNR	High illuminance	dB	47.2	51.0**	50.2**	46.2
	20lux	dB	28.5	35.1	34.2	31.2
	5lux	dB	21.0	28.7	28.1	24.2

*Linear FWC of 18,000e- @ Low CG mode

** High luminance SNR @ Low CG mode

Here is a theoretical calculation of SNR gap of two different correction methods. The noise is presented by

$$\mathrm{Noise}^2 = \frac{1}{8}\mathrm{n}_{\mathrm{AF}}{}^2 + \frac{7}{8}n_0{}^2 \qquad (1)$$

Where, n_{AF} and n_0 are the noise of AF pixels and normal pixels, respectively and PDAF density of 1/8. Plugging noise into SNR,

$$\mathrm{SNR} = 20\log\left(\frac{\sqrt{8}S}{n_0}\right) - 10\log\left(\frac{\mathrm{n}_{\mathrm{AF}}{}^2}{n_0{}^2} + 7\right) \qquad (2)$$

In conventional correction method, Green AF pixels are replaced to the average of 12 normal pixels and Red/Blue AF pixels are from 8, when assuming the BPC kernel of 7x7 and planar image. The noise of AF pixel in each channel are:

$$\mathrm{n}_{\mathrm{AF\_G}} = \frac{n_0}{\sqrt{12}},\ \mathrm{n}_{\mathrm{AF\_R,B}} = \frac{n_0}{\sqrt{8}} \qquad (3)$$

Total noise of AF pixel is:

$$\mathrm{n}_{\mathrm{AF}} = \sqrt{\frac{1}{2}\left(\mathrm{n}_{\mathrm{AF\_G}}\right)^2 + \frac{1}{2}\left(\mathrm{n}_{\mathrm{AF\_R,B}}\right)^2} = n_0\sqrt{\frac{10}{96}} \qquad (4)$$

Plugging (4) into (2), SNR of conventional method is:

$$SNR_{conventional} = 20\log\left(\frac{\sqrt{8}S}{n_0}\right) - 8.52dB \qquad (5)$$

In Dilution mode, noise of the normal pixels decreases by square root three times, coming from three horizontal binning. But, no noise attenuation in AF pixel. Therefore, the noise of AF pixel is:

$$\mathrm{n}_{\mathrm{AF}} \approx \sqrt{3}n_0 \qquad (6)$$

Plugging (6) into (2), SNR of Dilution mode is:

$$SNR_{Dilution} = 20\log\left(\frac{\sqrt{8}S}{n_0}\right) - 10dB \qquad (7)$$

The two calculated equation (5) and (7) resulted in a SNR gap of 1.5dB. There seems a slight difference between calculation and measurement result because the theoretical calculation was considered only PDAF correction, not for binning methods. In the measurement result, the conventional method is operating in analog binning, whereas Dilution mode is digital binning. Therefore, the additional ADC noise reduction seems to slightly improve SNR in dilution mode.

Conclusion

A 0.8um 108Mp CMOS image sensor, supporting Nona-Remosaic recently unveiled for mobile application as shown in **Figure 9**. And a new PDAF correction method, Dilution mode has been demonstrated to improve image quality in Nona-binning mode. In Dilution mode, the image quality, such as false color, broken line and dot artifact have dramatically improved and also scored much larger point in Corner Artifact Metric test. Therefore, CMOS image sensor in this work provides a significantly accurate and reliable AF performance without image quality degradation by PDAF density increase. We expect that Nonacell and Dilution mode will accelerate 'smaller pixel and more resolution' trends for mobile application beyond a hundred Mega-pixel image sensor.

Figure 9. Die image of 108Mp CMOS image sensor

References

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Author Biography

Yeongheup Jang received his BS in electronic engineering and computer science from Hanyang University (2007) and MS in electronic engineering from POSTECH (2009). Since then, he has been working in Samsung Electronics and his work is focused on the evaluation and verification of CMOS image sensor for mobile application

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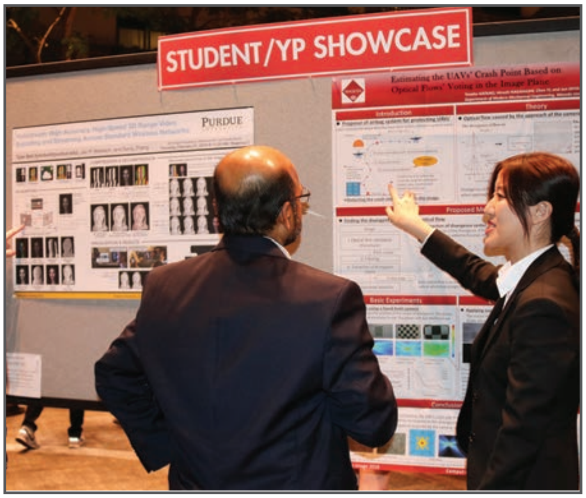

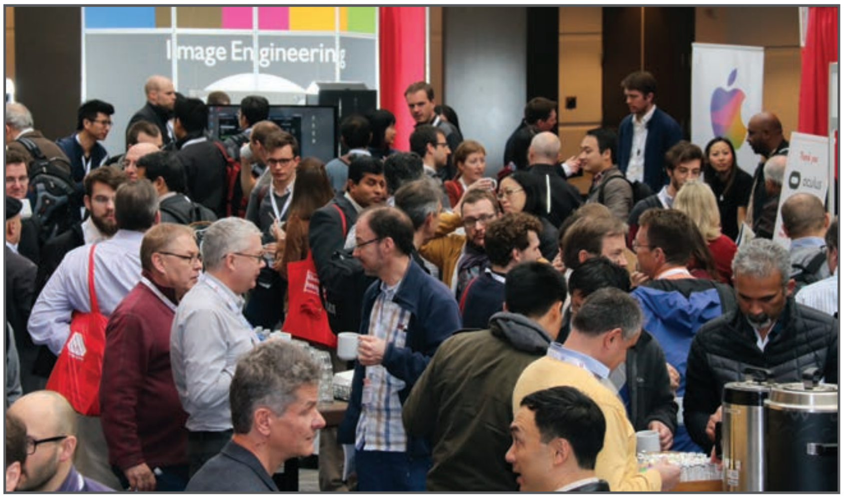

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