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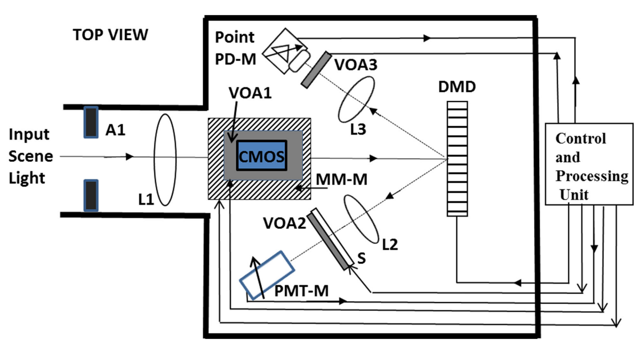

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Manuscript received November 28, 2018; revised March 28, 2019; accepted April 2, 2019. Date of publication April 4, 2019; date of current version April 24, 2019. This paper has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the author. The material consists of a video, viewable with VLC Media Player, demonstrating CAOS imaging for real-time (48 POI frame/second) laser beam tracking using POI Frame=1023 CAOS pixels and POI refresh time of 20.8 ms. The size of the video is 2.22 MB. Contact n.riza@ucc.ie for further questions about this work. Corresponding author: Nabeel A. Riza (email: n.riza@ucc.ie).

Abstract: For the first time, demonstrated is an extreme linear Dynamic Range (DR) Pixels of Interest (POI) [i.e., Coded Access Optical Sensor (CAOS)] Digital Single Lens Reflex (DSLR) camera design that engages three different types of photosensors within one optomechanical assembly to smartly identify POI across a one billion to one light irradiance range. A pixelated CMOS sensor provides a limited DR and linearity image by engaging a moveable mirror placed between the Digital Micromirror Device (DMD) and the frontend imaging lens. Next using DMD control, non-POI light is directed away from the chosen point photodetector (PD) engaged for high DR POI image recovery, giving the PD an improved use of quantum well capacity. For brighter POI, a solid state photodiode point PD with an electronic gain controlled amplifier is engaged while for weaker light POI, a photomultiplier tube (PMT) with variable optical gain is deployed. POI imaging is achieved using time-frequency CAOS modes via DMD control and time-frequency correlation and spectral digital signal processing. A 123.4 dB linear DR POI recovery is achieved for a custom incoherent white light 36-patch target while a record 177 dB linear DR recovery is demonstrated for a single patch 633 nm laser target. For the first time, a 1023 POI frame, real-time 48 frames/s update rate CAOS imaging is demonstrated for tracking a changing focal spot moving laser target.

Index Terms: Optical imager, camera, digital micromirror device, high dynamic range imaging.

1. Introduction

In applications across automotive, surveillance, industrial machine vision, scientific and medical sectors, the image intensive modern world today is faced with certain extreme contrast and bright full spectrum light scenarios requiring critical target recognition and tracking. In such cases, optical imaging with linear extreme DR and sufficient Signal-to-Noise Ratio (SNR = Signal Optical Power/Noise Optical Power) for POI measurements is required for robust and true image data capture for mission critical decisions that can potentially be implemented by machine intelligence. For the visible spectrum, commercial silicon CMOS sensor makers very recently have announced linear DR sensors reaching 96 dB [1]. Earlier CMOS sensor attempts have reported higher DRs using multi-exposure and log-based sensing methods that are limited by non-linear and image processing artefact effects that not only restrict full range contrast detection but also degrade color capture

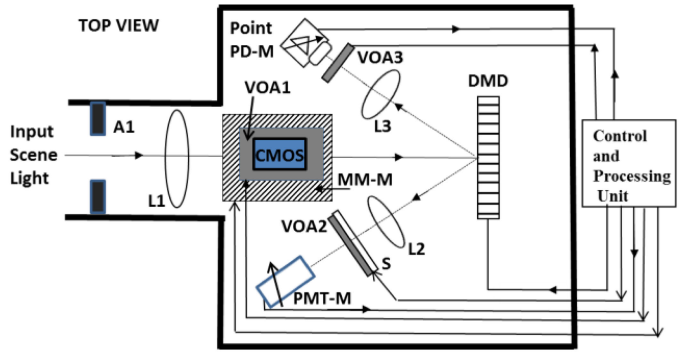

Fig. 1. Proposed DSLR CAOS camera using three different types of optical detectors.

[2]–[5]. These prior-art CMOS sensors fundamentally collect photo-charge per pixel independently to generate a DC current/voltage per pixel. On the other hand, recently proposed is the full spectrum CAOS camera based on the principles of multi-access Radio Frequency (RF) wireless network that uses image map light detection via AC time-frequency signal generation, DSP noise reduction and variable DSP processing gain to enable robust imaging with extreme linear DR and SNR control [6]. A prior CAOS camera design used the DMD to direct imaged light to the CMOS sensor that created image under-sampling as the DMD and CMOS sensor pixel grids were not 1:1 matched [7]. In addition, this CAOS design was tested with a limited 82 dB DR white light in-house constructed target that does not reach the typical 120 dB linear DR range common for natural scenes in night or bright sunshine conditions. Furthermore, the previous CAOS design was restricted to a 136 dB linear DR and non-automated operations that prevented real-time video generation [8]. The present paper counters these limitations of our prior CAOS imager designs by proposing and demonstrating a new three photo-sensor embedded DSLR CAOS camera design that empowers smart POI real-time robust SNR controlled imaging over a very wide 180 dB linear DR covering both very bright and very weak light targets.

2. DSLR CAOS Camera Design

Fig. 1 shows the proposed DSLR CAOS camera design using a solid-state point PD module (PD-M), a point PMT Module (PMT-M) & a 2-D CMOS sensor. Light to be imaged passes through a controlled aperture A1 and enters the camera via the front lens assembly L1. A Motorized Mirror Module (MM-M) is electrically controlled to either a flat mirror state so input light to be imaged goes to the DMD or is in a 45° tilt state to send light to the CMOS sensor, thus creating the CAOS DSLR design. CMOS imaged light after computer processing provides an initial POI map that is next imaged using both optical detection arms of the camera. Point PD-M images brighter POI while the PMT-M images the weaker light POI. A Variable Optical Attenuator (VOA) VOA2 and mechanical Shutter (S) are placed between the DMD and the PMT to prevent saturating bright light from entering the PMT to prevent damage. Lenses L2 and L3 perform imaging between the DMD plane and the PMT and PD-M, respectively. VOA1, VOA2 and VOA3 are used to optimize total light falling on the CMOS sensor, PMT-M, and PD-M, respectively. To best use the available quantum well capacity of the PD-M and PMT, non-POI light from the full input image is directly away from the engaged optical detector by using one of the two $\pm\,\theta$ tilt states of the micro-mirror setting of the DMD. The point PD-M detection arm is deployed first with all micro-mirrors of the POI on the DMD pointing to direct light to the PD-M to provide a total optical power reading for POI light that combined with initial CMOS sensor image data decides if the PMT should be engaged first or the point PD-M for image acquisition. Next, using the CAOS TDMA (Time Division Multiple Access) mode, light from individual pixels in the POI map are measured using DMD control and the chosen point detector. In the TDMA mode, the detector provides DC level light signals to give individual

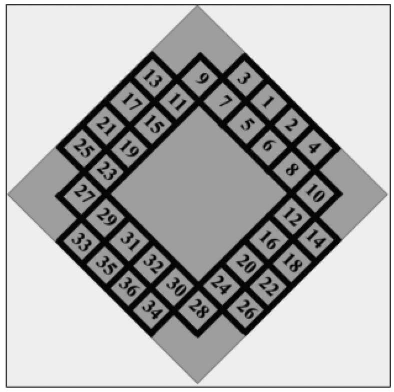

Fig. 2. Custom 36-Patch 160 dB DR target with numbered patches.

TABLE 1
DR Table for the 36 Patches

Patch #	DR (dB)	Patch #	DR (dB)	Patch #	DR (dB)	Patch #	DR (dB)
1	0	10	41.2	19	82.2	28	123.4
2	4.6	11	45.8	20	86.8	29	128
3	9.2	12	50.2	21	91.4	30	132.6
4	13.8	13	54.8	22	96.0	31	137.2
5	18.2	14	59.4	23	100.6	32	141.8
6	22.8	15	64.0	24	105.2	33	146.2
7	27.4	16	68.6	25	109.8	34	150.8
8	32.0	17	73.2	26	114.2	35	155.4
9	36.6	18	77.8	27	118.8	36	160

pixel optical power measurements. These measurements provide a limited SNR level irradiance map for the POI, enabling an individual pixels assessment of which CAOS modes [9] and which camera optical detection arms will be required for robust and extreme linear DR pixel irradiance recovery for the incident image.

3. Experiments and Discussion

Fig. 1 CAOS DSLR camera is built in the laboratory using the following components. Vialux DMD model V-7001, point PD Thorlabs PDA100A2, point PMT Thorlabs PMM02, Thorlabs CMOS camera model CS2100M-USB Quantalux sCMOS 2.1Mp, NI 16-bit DAQ card 6366, DELL 5480 laptop for control and DSP, Thorlabs variable Neutral Density (ND) filter VOAs, Thorlabs Iris S and Iris A1, and 2.54 cm diameter Thorlabs mirror. Lenses L1, L2, and L3 have focal lengths of 6 cm, 5 cm, and 5 cm, respectively. Inter-component distances are: 6.25 cm L1: DMD, 11.5 cm L2: DMD, 11.5 cm L3: DMD, 8.85 cm L2:PMT and L3:PD, 3 cm L1:MM, 3.25 cm MM:CMOS, 1 cm VOA:CMOS, 4 cm L1:A1, and 0.5 cm S:L2. Fig. 2 shows the Image Engineering (Germany) 36-patch white light custom target covering a 160 dB camera DR with patches arranged in a near circular format to minimize vignetting effects. DR in dB = 20 log (P_{max}/P_{min}), where P_{max} and P_{min} are the maximum and minimum optical power levels measured per imaged pixel. Here, for each optical irradiance measurement to be robust, one must meet an application relevant minimum SNR standard for light measurement per pixel (e.g., Human vision Rose criteria: SNR $\geq$ 5) [10]. With an SNR = 1, one produces the maximum possible DR and this DR number is typically used for CMOS/CCD/FPA sensors, particularly for machine vision. Table 1 shows the designed DR in dB for each patch in the target with patch 1 being the reference patch that has maximum light throughput. These

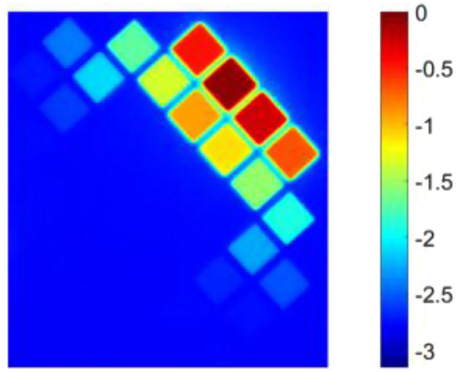

Fig. 3. CMOS sensor generated image of the 36-patch target.

TABLE 2
Measured Target Patch DR Values

Patch #	D (dB)	M (dB)	SNR	Patch #	D (dB)	M (dB)	SNR
1	0	-	517	11	45.8	40.8	4.7
2	4.6	3.7	336	12	50.2	44.1	3.2
3	9.2	8.1	203	13	54.8	47	2.3
4	13.8	12.1	129	14	59.4	49.4	1.7
5	18.2	16.7	75	15	64.0	50.9	1.48
6	22.8	21.1	45	16	68.6	52.2	1.27
7	27.4	25.3	28	17	73.2	52.99	1.16
8	32.0	29.5	17.3	18	77.8	53.6	1.07
9	36.6	32.8	11.8	19	82.2	54	1.036
10	41.2	36.8	7.4	20	86.8	54.2	1.008

patches, each 1.5 cm $\times$ 1.5 cm are constructed with specific custom attenuation filters. The target plate is placed in a LED driven white light illumination box with a total illumination setting of 6311 kLux. The target box is placed at a distance of 156 cm from L1. The stability of the high power LED lightbox model LG3 illuminating all the patches is controlled to a level of 1/4000 or 0.25%.

The DSLR CAOS camera operation is first tested with the incoherent light 36-patch target. Light emerges only through the 36 patches and is imaged onto the CMOS sensor using L1 and the mirror in the 45° position. Given the target bright pixels are saturating the CMOS sensor, sensor integration time is reduced to 0.592 ms. Here VOA1 is set for a zero OD (Optical Density) optical attenuation. A1 is set to a 9 mm diameter for best clarity image capture.

These settings allow the first non-saturated target image capture shown in Fig. 3 using a log scale for better visualization. Any increase in integration time creates spill over from the saturated patch 1. The CMOS sensor provided image is electronically processed to determine the Measured (M) DR readings (see Table 2) for each detected patch of target. SNR is computed as follows. Signal power is computed by taking the average of 70 $\times$ 70 CMOS pixels comprising the central region of the imaged patch. Noise power is computed by taking the average of 70 $\times$ 70 CMOS pixels at the bottom left corner of the acquired Fig. 3 image where spatial noise is dominant. A total of 8 patches are considered reliable imaging based on the fact that there is a difference of $\leq$3.1 dB between Designed (D) patch DR and measured patch DR, indicating robust image recovery up to the 32 dB DR patch 8. The CMOS sensor DR is specified as 87 dB, but no information is provided about its linear DR performance. This state-of-the-art high DR CMOS sensor provides highly inaccurate scaled light power readings for patches that it registers as detected. For example, it measures a 53.6 dB DR for patch 18 which has a 86.8 dB DR. Clearly, high DR robust patch

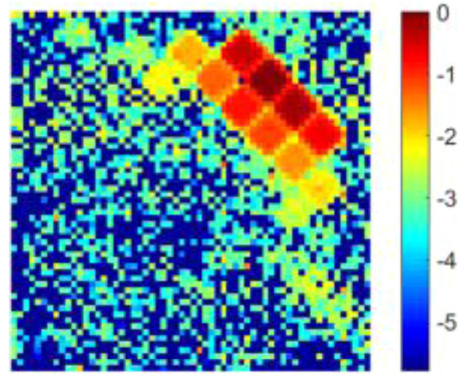

Fig. 4. CAOS CDMA-mode Target capture is up-to 54.8 dB DR patch 13.

TABLE 3
Measured Patch DR Values

Patch #	D (dB)	M (dB)	SNR	Patch #	D (dB)	M (dB)	SNR
1	0	-	1205	8	32.0	31.3	32.9
2	4.6	4.63	708	9	36.6	33.8	24.6
3	9.2	8.65	454	10	41.2	40.7	11.9
4	13.8	13.67	250	11	45.8	43.8	7.8
5	18.2	17.08	169	12	50.2	49.2	4.2
6	22.8	22	96	13	54.8	53.8	2.4
7	27.4	25.9	61				

recovery becomes a challenge for this CMOS sensor leading to erroneous and non-linear gray-scale image capture that can have serious consequences in some high linear contrast imaging applications. Nevertheless, the CMOS sensor provides an image for the CAOS DSLR camera to calculate the POI spatial locations data map on the DMD that is next used to engage the second step in the DSLR imaging operations with the mirror put in its flat state. Specifically, the POI map used is a 60 $\times$ 60 CAOS pixels grid with each CAOS pixel made up of 9 $\times$ 9 micro-mirrors. Given the 160 dB DR limit of the white light test target with extremely low light patches, the PMT arm of the camera is engaged to recover the 36 patch target given the PMT's larger gain and higher output voltage signal capability feeding the DAC port. All remaining DMD micro-mirrors outside the POI map are set to direct light away from the PMT. The DMD is first operated to engage the CAOS TDMA mode with a time slot per CAOS pixel of 1 ms. The PMT has an electronic bandwidth of 20 KHz. The PMT intrinsic optical gain is set to produce a maximum voltage signal near 10 V to match DAC input limit and this happens when light from all patches is incident on the PMT. The DAQ operates at 100 Ksps. As the TDMA-mode collects light via the PMT on a single CAOS pixel per time interval basis with DC electrical signal generation that is noisy for the low light patch pixels, only 2 patches are robustly (SNR $\geq$ 2) detected. Increasing PMT optical gain does not benefit signal recovery as it increases both signal and noise light and does not boost SNR. For each imaged patch zone, the average signal power is computed by take the average of the 16 brightest CAOS pixels in a 25 CAOS pixels patch identifying zone. The average noise power is computed by taking the average of the non-zero optical power CAOS pixels taken from a group of 25 CAOS pixels. These pixels are in the noisy region of the reconstructed image where there is no patch recovery.

One way to improve SNR of the optical detection process is to engage the CAOS CDMA (Code Division Multiple Access) mode [11] where all POI are simultaneously time modulated by their unique but zero cross-correlation time sequence codes, e.g., using a 4096 on-off (i.e., 1's and 0's)

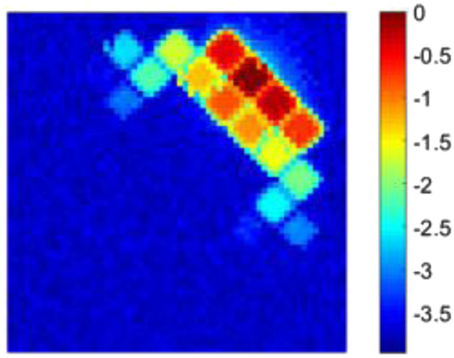

Fig. 5. CAOS FM-TDMA-mode capture up-to 73.2 dB DR patch 17.

TABLE 4
Measured Target Patch DR Values

Patch #	D (dB)	M (dB)	SNR	Patch #	D (dB)	M (dB)	SNR
1	0	-	4700	10	41.2	40.9	42
2	4.6	4.68	2800	11	45.8	44	30
3	9.2	8.58	1760	12	50.2	50.0	15
4	13.8	13.86	958	13	54.8	53.11	10
5	18.2	17.06	660	14	59.4	59.9	5
6	22.8	22.02	370	15	64.0	61.53	4
7	27.4	25.9	240	16	68.6	66.2	2.3
8	32.0	31.4	127	17	73.2	70.1	1.5
9	36.6	34.5	89	18	77.8	72.91	1.1

bits Walsh sequence. In this case, the average instantaneous total optical power incident on the PMT is high enough to maintain adequate SNR time correlation processing based patch irradiance recovery. Note that for irradiance decoding, the encoded point PD signal is auto-correlated with its CAOS pixel specific equivalent 4096 on-off (i.e., 1's and −1's) bits Walsh sequence to produce the scaled pixel irradiance value. Fig. 4 shows the recovered log scale image indicating robust (SNR $\geq$ 2.4) for 13 patches of the target indicating a measured patch 13 DR of 53.8 dB vs the 54.8 dB design. The CDMA bit rate is 1 Kbps and the DAC sampling rate is 100 Ksps. Compared to the CMOS sensor provided image data with a near 32 dB DR accurate image irradiance extraction up-to patch 8, Table 3 shows that the CAOS CDMA-mode enables a much higher 54 dB DR and robustness to image recovery. To implement even weaker light patches recovery, the higher DR CAOS Frequency Modulation (FM) TDMA mode is engaged where each time slot contains an FM carrier signal, in this case, a 520 Hz frequency square wave carrier that undergoes DSP-based RF spectrum analysis using the Fast Fourier Transform (FFT) algorithm implemented in the laptop processor. DSP FFT gain in dB is given by 10log (N/2) where N is the number of samples in the sampled photo-detected signal and equivalently in the FFT. N is of order 2^n where n is an integer. FFT filter 3-dB bandwidth in Hz is the inverse of the total sampling duration in seconds. Again using the same 60 $\times$ 60 CAOS pixels grid and then using a DAQ sampling rate of 65536 sps for a TDMA time slot of 1 second giving $N = 2^{16}$ samples, a DSP gain of 45 dB and FFT filter 3-dB bandwidth of 1 Hz is used to extract the pixel irradiance stamped carrier signal from noise, thereby also controlling the CAOS pixel measurement SNR for a robust irradiance retrieval.

With all patches viewed using the CAOS FM-TDMA mode, compared to the CMOS sensor and CAOS CDMA-mode images, Fig. 5 shows the recovered target patch robust imaging up to a much improved patch number 17 with a measured patch DR of 70.1 dB given the designed DR of 73.2 dB.

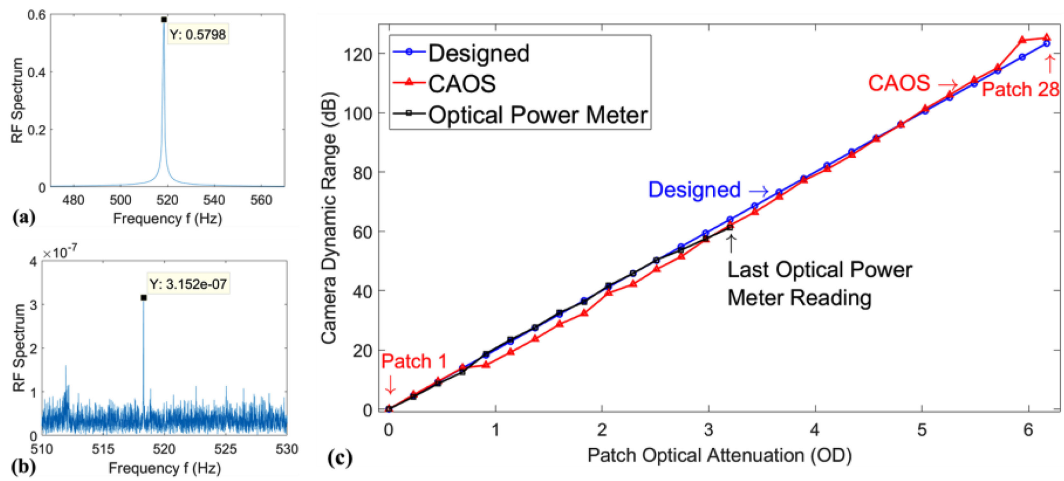

Fig. 6. CAOS FM-TDMA mode FFT traces for individually imaged target patches. (a) Patch 1 is 0 dB DR Brightest Patch with SNR = 100. (b) Patch 28 with Design DR 123.4 dB, Measured DR 125.3 dB, SNR = 9.4. (c). FM-TDMA mode 36-patch target optical image recovery linearity and robustness data with a designed versus measured curve fitted slope values of 20 dB/OD and 20.66 dB/OD, respectively.

Table 4 shows the designed versus measured DR for all the recovered patches with SNR $\geq$ 1.5. Based on the Table 4 data, one can conclude that the FM-TDMA mode unrecovered higher DR patches are receiving optical spatial crosstalk noise light contributions from the brighter patches in the target creating an SNR $<$ 1. This spatial noise is caused by the limited quality of the L1 imaging system for the specific Image Engineering (Germany) lightbox illuminator conditions and deployed patch material target scattering properties. To test this hypothesis and measure the experimental extraction power of the FM-TDMA mode, all patches are spatially blocked except for the target patch under measurement. The CAOS pixel size is chosen to be 30 $\times$ 30 micro-mirrors so it can cover the full individual patch area under time multiplexed observation. The DSP gain is increased to 57.2 dB using $N = 2^{20}$ over a 2 sec sampling window giving a 0.5 Hz FFT filter 3-dB bandwidth with a DAQ voltage range of 10 V for patches 1 to 4 and 1 V for other patches. In this case, recovery is up to patch 24 with a designed DR of 105.2 dB and a measured DR = 106 dB. Patch 25 with a designed DR of 109.8 dB is recovered at a measured DR = 111 dB by increasing the sampling time to 8 seconds (a narrower 0.125 Hz FFT filter 3-dB bandwidth) with $N = 2^{22}$ giving a higher DSP gain of 63.2 dB. Finally, Patch 27 and Patch 28 are recovered by increasing the sampling time to 128 seconds (giving an even narrower 7.8 mHz FFT filter 3-dB bandwidth) and $N = 2^{26}$ giving a further increased DSP gain of 75.3 dB. Patch 28 has a designed DR of 123.4 dB and a measured DR = 125.3 dB. The measured patch DR dB results for all 28 patches maintain an SNR $\geq$ 9.4. Clearly control of both DSP gain and FFT filter bandwidth provide programmable SNR control for the patch irradiance measurements. For a given application scenario, DR needs are known. Hence the CAOS camera will have application dependent preset parameters. For the Fig. 6 data, the signal power is the FFT peak value of the CAOS pixel reading. The noise power is calculated by take the average of 200 FFT readings surrounding the FFT peak. Using these signal and noise values, the FM-TDMA mode SNR is computed.

Fig. 6 shows example FFT traces that provide the CAOS pixel imaging data including measured DR and SNR. Also shown are linearity and robustness of the measured DR using the described CAOS FM-TDMA mode for the 36-patch target over a 125 dB DR range. In addition, shown are the designed DR numbers for the patches and a Newport model 2391-C power meter measured DR numbers obtained by recording the optical powers at the individual patches at the DMD plane while blocking all the other patches at target plane that are not under measurement. These power meter-based optical power readings allow reliable measurements up to patch 15, after which the

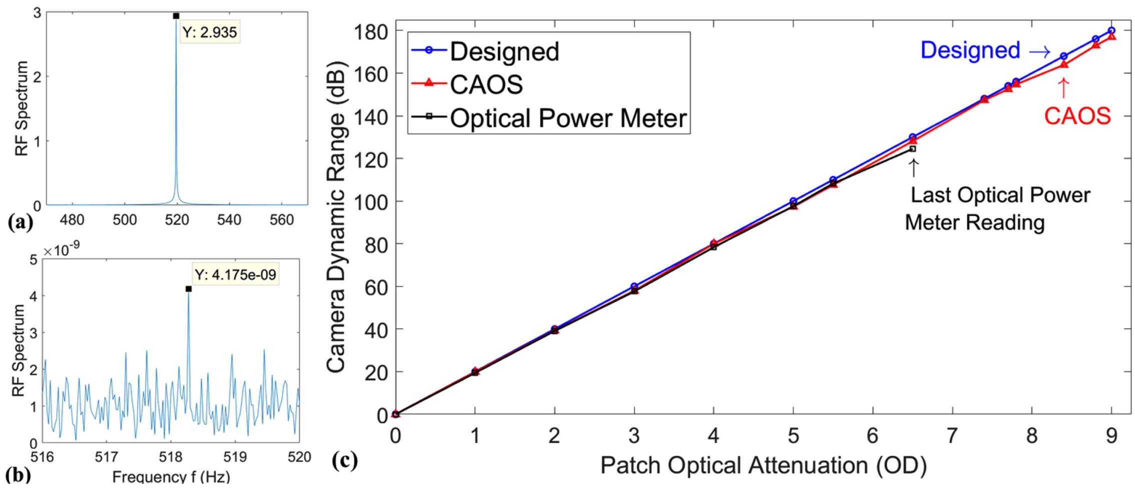

Fig. 7. Laser driven single image patch CAOS FM-TDMA mode FFT RF peaks. (a) Laser patch 0 dB design DR, SNR = 269. (b) Laser patch 180 dB design DR, 177 dB measured DR, SNR = 4 (c). CAOS FM-TDMA mode single laser driven patch target optical image recovery linearity and robustness data with the designed versus measured curve fitted slope values of 20 dB/OD and 19.71 dB/OD, respectively.

optical power falls below 10^{-9} W and gives unreliable readings. For the CAOS FM TDMA-mode data measured and shown in Fig. 6 as a plotted DR curve, a near linear and robust image pixel recovery operation up-to a measured 123.4 dB DR is achieved. Note that both the x and y axes of this linearity data are log scales. Here OD value is the log of the optical attenuation factor for a given patch, so for a designed 10^6 attenuation, the OD = 6. Recall that CAOS FM-TDMA mode deploys a narrowband FFT filter via DSP operations on the PD provided AC input signal, thus only allowing a fraction of the optical noise to enter into an irradiance measurement. Indeed, DSP noise filtering is a unique feature of CAOS imaging. When comparing the Fig. 5 and Fig. 6 CAOS FM-TDMA mode data sets, one correctly concludes that the L1 front lens imaging system produces inter-patch spatial crosstalk optical noise at the DMD image plane. This crosstalk noise causes patches with higher DR values (i.e., patch 18 and higher) to have SNR $\leq$1.1, preventing CAOS FM-TDMA mode robust pixel recovery beyond patch 17 when no physical blocking of surrounding patches is deployed during CAOS imaging. Thus, an optimized L1 lens is required to minimize target inter-patch crosstalk at the DMD plane, and this will be done in future works. In addition, note that the lightbox LEDs have 32 KHz temporal modulation that was set to a 95% duty cycle. Such a modulation introduces temporal noise within the FFT filter, further limiting DR recovery. To test the detectable DR limit for the built CAOS camera without use of the spatial optical crosstalk causing lens L1, a laser driven single image patch target is created using a 13.7 mW CW He-Ne laser beam directly illuminating the DMD with the VOA3 acting as a variable optical attenuator providing a 10^9:1 optical power suppression range to test a 180 dB linear DR range. Given the bright laser light conditions, the solid-state point PD sensor is used versus the light sensitive PMT. Hence, the shutter is engaged so no laser light reaches the PMT. The CAOS pixel size is chosen to be 100 $\times$ 100 micro-mirrors so it can cover the full individual laser patch area on the DMD. Fig. 7 shows the extreme FFT trace readings obtained using the FM-TDMA mode, indeed showing a measured 177 dB DR for the experimental camera. In this case, a NI model 6211 16-bit DAQ card is used and 60 dB variable electronic gain amplifier of the point PD is engaged. Fig. 7(a) data is obtained using the point PD amplifier gain at 0 dB and a DAQ voltage range setting of 10 V with sampling rate of 26214 sps for 5 seconds giving a DSP gain of 48.2 dB and FFT bandwidth of 0.2 Hz. The Fig. 7(b) data is obtained using the point PD amplifier gain at 60 dB and a DAQ voltage range setting of 0.2 V with sampling rate of 209715 sps for 40 seconds giving a DSP gain of 66.23 dB

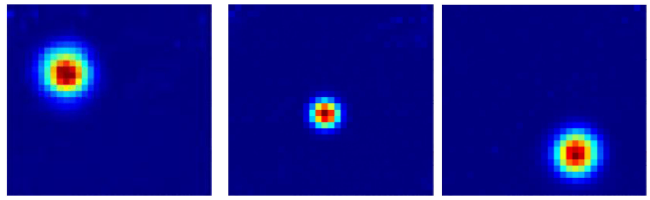

Fig. 8. Demonstration of CAOS imaging for real-time (48 POI frame/second) laser beam tracking using POI Frame = 1023 CAOS pixels and POI refresh time of 20.8 ms. Shown are 3 different POI frames within a 20 seconds recording of 960 POI frames. Video provided in supplemental files.

and FFT bandwidth of 0.025 Hz. Fig. 7(c) shows the linearity of the DR measurements versus the design DR due to the Optical Density (OD) value of the ND filters used in VOA3. No other VOAs are engaged so one can generate the 180 dB extreme linear DR imaged light patch conditions. The output of the point PD amplifier feeds the DAQ. Hence, the FFT peak data has to be scaled based on the specific electronic amplifier gain used per measurement before plotting the data. Fig. 7 is a log scale vs log scale plot (like Fig. 6) and shows the near linear DR response of the CAOS camera demonstrating a record measured 177 dB linear DR for CAOS FM-TDMA-mode laser driven patch optical irradiance recovery with SNR $\geq$ 4.

For a moving target, the target distance and speed, and camera pixel size will determine the maximum sampling window that can be used to resolve target motion. Lasers are a common source for active imaging and tracking applications. To test this active tracking capability, the CAOS camera is automated. The camera next views a laser beam that moves laterally but also changes its beam spot diameter. This action was achieved using a off-center placement of an electronically controlled variable focus liquid lens in a laser beam path impinging on the camera. The liquid lens is set for a focus sweep rate of 0.1 Hz. Using the CAOS CDMA mode with 1023 (or 31 $\times$ 33) POI frame and 1024 bits Walsh time sequences at 50 Kbps per CAOS pixel, a 48 POI frame/second imaging (i.e., POI refresh time of 20.8 ms) is achieved. For a 20 seconds recording time with 960 POI frames, Fig. 8 shows 3 sample POI frames highlighting the changing laser beam spot diameter and location of beam within the viewed scene. This is the first report of real-time (i.e., better than the classic 30 frames/sec) video imaging by the CAOS camera.

4. Conclusion

Reported for the first time are (a) a record 177 dB linear DR response of the CAOS camera using a controlled brightness laser driven pixel and signal extraction using dual gains of electronic amplification and DSP spectrum analysis and filtering, (b) a 123.4 dB linear DR with controlled SNR $\geq$ 9.4 robust irradiance capture via the CAOS camera of an image test industry custom designed white LED driven 36-patch target and (c) a real-time (48 POI frames/sec) laser beam tracking operations (POI frame = 1023 CAOS pixels) of an automated software controlled CAOS camera. These three new results highlight the flexibility and controlled signal processing powers within the CAOS camera for robust and extreme linear DR optical imaging across diverse applications such as automotive and surveillance. It is also shown that the deployed state-of-the art high DR CMOS sensor fails to provide high linear DR and reliable image data and the measured DR using CAOS FM-TDMA mode full target view imaging is limited by the inter-patch spatial noise from the used frontend lens and not the CAOS-mode.

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