General Description

The epc610 chip is a general purpose, monolithic, fully integrated photoelectric CMOS device for optical distance measurement and object detection. Its working principle is based on the three-dimensional (3D) time-of-flight (TOF) measurement.

The system-on-chip (SOC) contains:

- A full data acquisition path with the driver for the LED, the photo-receiver with an 8x8 pixel TOF CCD array, the signal conditioning, the A/D converter and the signal processing.
- An on-chip controller managing the data acquisition and the data communication.
- An SPI interface for the command and data communication.
- A supply-voltage power management unit.

Together with a microprocessor and few external components, a fully functional TOF camera can be built. It measures the object distance individually and simultaneously per pixel. Every pixel contains also the brightness and the ambient-light information from the object.

The working principle is based on the elapsed time-of-flight (TOF) of a photon (modulated light) emitted by the transmitter (LED) and reflected back by the object to the photosensitive receiver. The receiver computes the "time-of-flight" distance from the time difference in each pixel individually.

The very high photosensitivity allows operating ranges up to several meters and an accuracy down to a centimeter depending on the lens and the illumination power.

Features

- 8x8 pixel TOF CCD array for low cost application.
- Complete data acquisition system for distance measurement or object detection on chip. Allows for minimum part count designs.
- On-chip high power LED driver.
- Easy to use operation in combination with a microprocessor.
- Integrated signal-processing.
- Response time of less than 1ms possible.
- Output data: 12 bit sample data per pixel.
- Excellent ambient-light suppression up to >100kLux.
- Integrated ambient-light meter ("Luxmeter") e.g. for brightness control or dimmer functions.
- Voltage supply with low power consumption.
- SPI interface for command and data transfer.
- Fully SMD-compatible flip-chip CSP24 package with very small footprint.

Applications

- Low cost 3D TOF camera
- People and object counting sensor
- Door opening, machine control and safeguard sensor
- 3D limit and proximity switch. Area scanner
- 3D distance measurement gauge
- Volumetric mapping of objects
- Automatic vehicle guidance
- Low cost seating position detection in cars
- Gesture control (man-machine-interface)

Functional Block Diagram

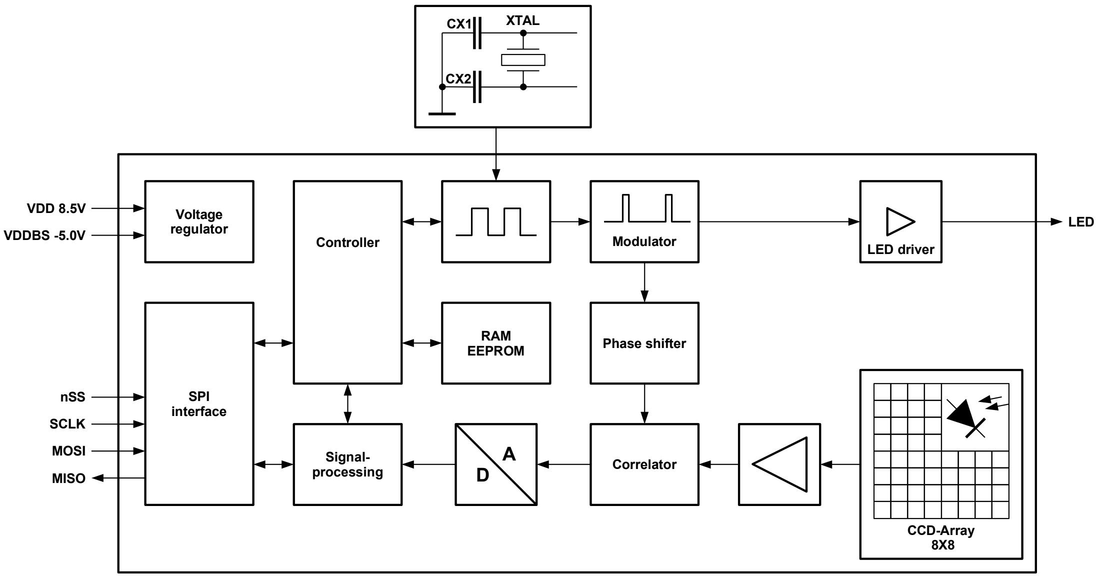

Figure 1: epc610 on-chip data acquisition system for 3D TOF cameras

Dear user, ESPROS Photonics is constantly striving to provide comprehensive and correct product information. Therefore, please check our website regularly for updated versions of this datasheet: www.espros.ch

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Absolute Maximum Ratings (Note 1, 2)

Supply Voltage V_{DD}	-0.5V to +9.5V
Voltage to any pin except V_{DD} according voltage class V_{SC} (Note 3)	-0.3V to V_{SC}+0.3V
Storage temperature (T_A)	-65°C to +150°C
Soldering Lead Temperature (T_L), 4 sec	+260°C

Operating Ratings

Operating temperature (T_A)	-20°C to +65°C
Humidity, non-condensing	5% to 95%

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Recommended operating conditions indicate conditions for which the device is intended to be functional, but do not guarantee specific performance limits. For guaranteed specifications and test conditions, see Electrical Characteristics.

Note 2: This is a highly sensitive CMOS mixed signal device with an ESD rating of JEDEC HBM class 2 (2kV to < 4kV) except for the pins VDD, VDDIO and SCLK with an ESD rating of JEDEC HBM class 1B (0.5kV to < 1kV). Handling and assembly of this device should only be done at ESD protected workstations.

Note 3: For voltage classes V_{SC} refer to Figure 4 and Table 4.

Electrical Characteristics

Operational Ratings - unless otherwise specified.

Symbol	Parameter	Conditions / Comments	V_{SC}	Min.	Typ.	Max.	Unit
V_{DD}	Supply voltage at VDD		8.5V	+8.0	+8.5	+9.0	V
V_{DD-PP}	Ripple on V_{DD}	peak-to-peak	8.5V			100	mV
$I_{DD-Average}$	Supply current	DC average , excl. LED driver current	8.5V			20	mA
$I_{DD-Peak}$	Supply current	peak, excl. LED driver current	8.5V			30	mA
V_{DDBS}	Bias voltage	no drift allowed	-5.0V	-4.9	-5.0	-5.1	V
$V_{DDBS-PP}$	Ripple on V_{DDBS}	peak-to-peak	-5.0V			50	mV
I_{DDBS}	Bias current		-5.0V			1.0	mA
V_{LED}	Voltage at LED	maximum	5.0V			5.0	V
I_{LED-ON}	Sink current at LED	open drain driver	5.0V			180	mA
V_{LED-ON}	Forward voltage at LED	@ I_{LED-ON} = 180mA	5.0V		200		mV
$V_{Digital-OH}$	Output high voltage	at digital pins, e.g. nSS, SCLK, etc.	5.0V	4.5		5.2	V
$V_{Digital-OL}$	Output low voltage	at digital pins	5.0V	0		0.5	V
$I_{Digital-OH}$	Output current	at digital pins, average	5.0V			0.1	mA
$I_{Digital-OL}$	Output current	at digital pins	5.0V			8.0	mA
$C_{Digital-Out}$	Load capacitance		5.0V			30	pF
$V_{Digital-IH}$	Input high voltage	at digital pins	5.0V	4.0		5.0	V
$V_{Digital-IL}$	Input low voltage	at digital pins	5.0V	0		1.0	V
$I_{Digital-In}$	Input leakage current	except VDDT, DC	5.0V			1.0	µA
$I_{Digital-In}$	Input current	at VDDT; DC	5.0V		42		µA
R_{DOWN}	Termination resistor	at VDDT; pull-down resistor	5.0V		120		kΩ
$C_{Digital-In}$	Input capacitance		5.0V			3	pF

Table 1: Electrical characteristics

Timing and optical Characteristics

Operational Ratings - unless otherwise specified.

Symbol	Parameter	Conditions / Comments	Min.	Typ.	Max.	Unit
t_{ON}	Power-up rise time	at VDD	1		10	ms
t_{INIT}	Start-up time				100	ms
t_{OFF}	Power drop-down time	at VDD	1		10	ms
f_{XTAL}	Center frequency	of the crystal oscillator (or ceramic resonator)		4		MHz
Δf_{XTAL}	Frequency deviation	of the oscillator, any deviation is added as a linear distance error			±100	ppm
$\Delta \varphi_{XTAL}$	Phase jitter	of the oscillator, peak-to-peak, cycle to cycle			50	ps
f_{SCLK}	Clock frequency	of SCKL, SPI interface			10	MHz
t_{SCLK}	Cycle time	of SCKL, SPI interface, SCKL = $1/f_{SCLK}$	100			ns
t_H / t_L	HIGH / LOW period	of SCKL, SPI interface, (refer to Figure 28)	50ns		1.0ms	ns
f_{MOD}	LED modulation frequency at pin LED	see Figure 15,	1.25		20	MHz
$t_{LED\text{-}rise/fall}$	Required rise/fall time of the illumination LED	@ 50 ohm load Remark: Use high speed LEDs with short switch-ing times e.g. Osram SFH4059, Vishay VSMB2000, Stanley DNK5306, etc.			12	ns
A_{PIX}	Photosensitive area	of one pixel		40x40		µm
A_{SENSOR}	Photosensitive area	of the sensor		320x320		µm
S_{AC}	AC sensitivity (conversion rate)	for distance measurement (modulated light), refer to Table 3 and Figure 15, @ λ = 850±50nm, Integration time = 103 µsec.		31		$\frac{nW/cm^2}{LSB}$
S_{DC}	DC sensitivity (conversion rate)	for ambient-light measurement (unmodulated light), refer to Table 3 and Figure 15, @ λ = 850±50nm, Integration time = 103 µsec.		12.3		$\frac{nW/cm^2}{LSB}$
A_{AC}	Received modulated light amplitude	dynamic range for distance measurement	50		1'000	LSB
A_{DC}	Ambient-light amplitude	dynamic range for ambient-light measurement	50		1'000	LSB
E_{Sup}	Ambient-light suppres-sion	@ λ = 850±50nm, Integration time = 103 µsec, total power on sensor area	40 64			W/m^2 nW/pixel
λ_{max}	Peak wavelength	maximum sensitivity, see Figure 2		850		nm
λ	Wavelength range	operating range	550		1'000	nm
$\varphi_{50\%}$	Half angle	see Figure 3		±60		deg

Table 2: Timing and optical characteristics

Symbol	Parameter	Conditions / Comments	Min.	Typ.	Max.	Unit
t_{INT}	Integration time	refer to , see Figure 15 programmable in 16 binary steps	1.60		52'600	µs
t_{MEAS}	Measurement time		0.8 0.261	1.2 0.665	212 210	ms
DR	Dynamic range	fixed integration time using integration times 1.6µs, 13.2µs, 205µs using the full range of integration times	32	 80	 110	dB dB dB
D_{UA}	Operating range	unambiguity range, @10MHz LED modulation frequency			15.0	m
ΔD_{RES}	Distance resolution	@10MHz LED modulation frequency, ≙ 1 LSB	0.5			cm
ΔD	Distance noise	single shot, 1σ value, ratio ambient-light : modulated light < 60dB ratio ambient-light : modulated light < 70dB for amplitude values inside AC dynamic range		 2.0 9.6		 cm cm
D_{OFFSET}	Distance offset	compensation to be done by the external micro-processor				
ΔD_{DRIFT}	Distance drift	@ temperature range from -20°C to +65°C, compensation to be done by the external micro-processor				

Table 2 cont.: Timing and optical characteristics

Other Parameters

Operational Ratings and λ = 850±50nm, AOI = 0°, LED modulation frequency = 10MHz - unless otherwise specified.

Sensitivity: epc610 @ integration time 103µs	**with optical bandpass filter** **640nm ± 27.5nm**	 **860nm ± 32.5nm**	 **940nm ± 30nm**	**without filter** **sunlight equivalent**
max. AC amplitude (1000 LSB)	407 nW/mm²	310 nW/mm²	407 nW/mm²	
min. ambient-light suppression E_{Sup}	53 W/m²			70 klx
		40 W/m²		69 klx
			53 W/m²	192 klx

Table 3: Sensitivity and ambient-light suppression vs. wavelength

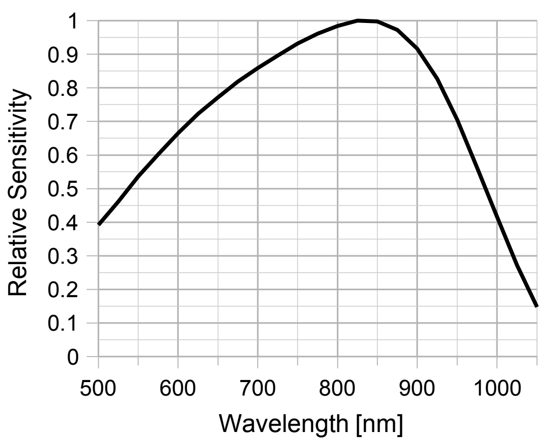

Figure 2: Relative spectral sensitivity (S_λ) sensitivity S_{AC} vs. wavelength

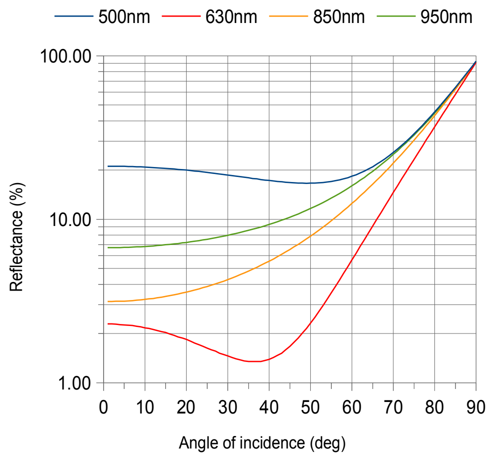

Figure 3: Reflectance vs. illumination angle (AOI)

Pin Configuration

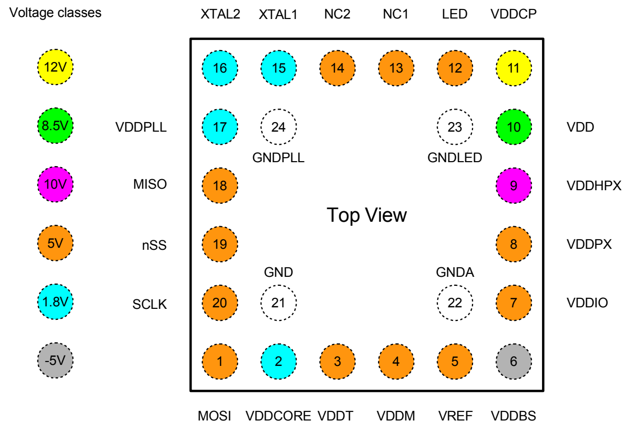

Figure 4: Pin configuration

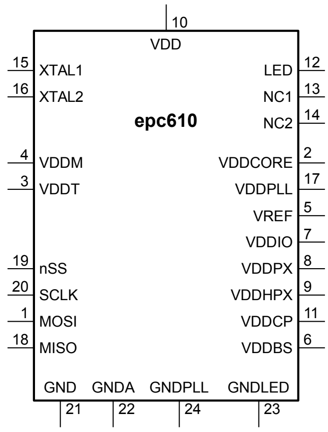

Figure 5: Schematic symbol

Pin Name	Pin No.	Type	V_{SC}	Description
nSS	19	DIN	+5.0V	SPI slave selection
SCLK	20	DIN	+5.0V	SPI serial clock input
MOSI	1	DIN	+5.0V	SPI serial data input
MISO	18	DOUT	+5.0V	SPI serial data output
LED	12	AOUT	+5.0V	LED driver output, high current, open drain, square-wave signal
XTAL1	15	AIN	+1.8V	Oscillator input, use only with crystal (or ceramic) oscillator
XTAL2	16	AOUT	+1.8V	Oscillator output, use only with crystal (or ceramic) oscillator
VDD	10	SUPPLY	+8.5V	Power supply +8.5V
VDDCORE	2	SUPPLY	+1.8V	Decoupling of internal digital core supply +1.8V
VDDPLL	17	SUPPLY	+1.8V	Decoupling of internal PLL supply +1.8V
VREF	5	SUPPLY	+5.0V	Decoupling of internal references +5.0V (not connected)
VDDIO	7	SUPPLY	+5.0V	Decoupling of internal internal I/O supply +5.0.0V
VDDPX	8	SUPPLY	+5.0V	Decoupling of internal internal pixel reference voltage +5.0V
VDDHPX	9	SUPPLY	+10V	Decoupling of internal internal pixel reference voltage +10V
VDDCP	11	SUPPLY	+12V	Filter capacitor pin for the charge pump circuit +12V
VDDBS	6	SUPPLY	-5.0V	Power supply: Bias voltage -5.0V
VDDM	4	DIN	+5.0V	Connect to +5.0V.
VDDT	3	DIN	+5.0V	Connect to +5.0V.
GND	21	SUPPLY	---	Ground for digital circuitry +1.8V
GNDA	22	SUPPLY	---	Ground for analog circuitry, charge pumps and +5.0V I/O circuit
GNDPLL	24	SUPPLY	---	Ground for PLL
GNDLED	23	SUPPLY	---	Ground for LED driver
NC1	13		+5.0V	Attention: Do not connect this pin
NC2	14	AIN	+5.0V	Connect this pin with zero ohm resistor to GND

Table 4: Pin function descriptions

Abbreviations to Table 4:

V_{SC} Supply class for matching components and I/O voltage levels
DOUT Digital output
DIN Digital input
AOUT Analog output
AIN Analog input

Layout information

CSP-24 Package (all measures in mm, ⊕⊐)

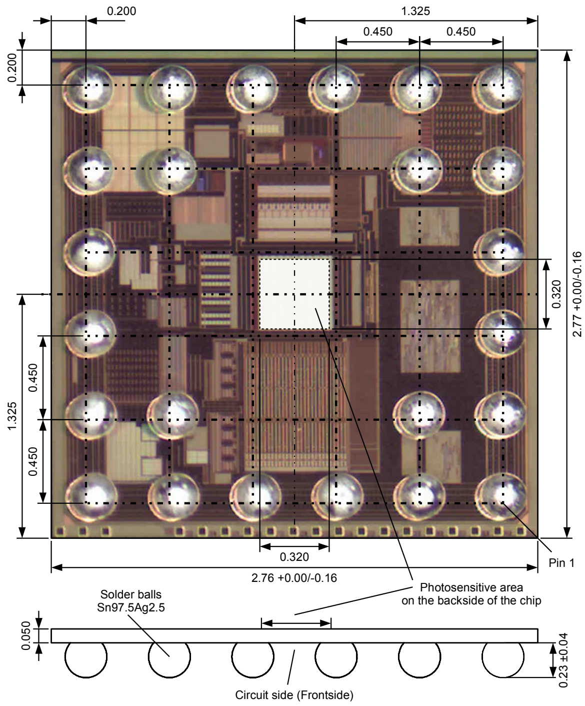

Figure 6: Mechanical dimensions

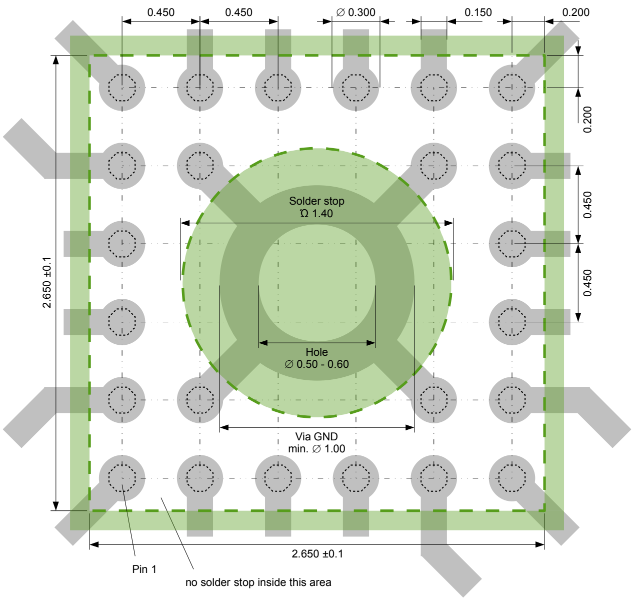

Figure 7: Layout recommendation

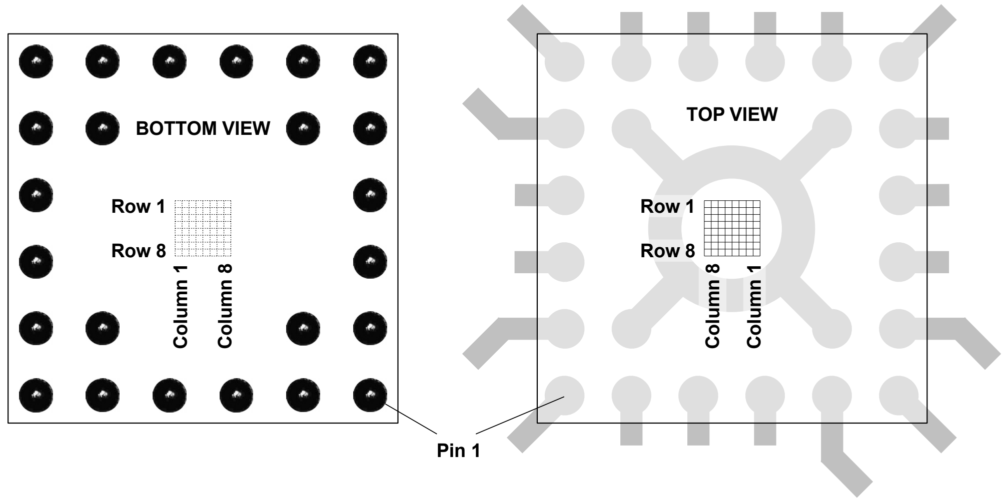

Figure 8: Orientation of the pixel field

Recommendations for a strong ground connection and for reliable soldering of solder balls:

- Use a pad layout similar to Figure 7. Notice all tracks should go underneath the solder mask areas.
- To keep the noise floor low in the sensitive receiver path of the chip, a low ohmic and low inductive connection to the supply ground is needed. Figure 7 suggests a recommended grounding of the chip (if a ground plane is not feasible):
  Feed all grounds into a central via-hole with a drill diameter 0.5 - 0.60mm.
- No additional connects to any pins inside of the opening of the solder mask.
- Open vias underneath the chip must be covered with a solder-stop lid, to prevent ascending solder during the soldering process.
- Refer also to our application note AN04 and AN08 Assembly of Wafer Level Chip Scale (WL-CSP) Packages.

Design precautions

The sensitivity of the sensor area is very high in order to achieve a long operational range of the 3D TOF imager. Thus, the epc610 device is very sensitive to EMI. Special care should be taken to keep the chip away from the IR LED signal tracks and other sources which may induce unwanted signals.

ESD protection

Highly sensitive CMOS mixed signal devices are sensible to electrostatic discharge (ESD). Figure 9 shows the principle how each pin of the chip is protected against ESD over-voltages by the corresponding safety elements.

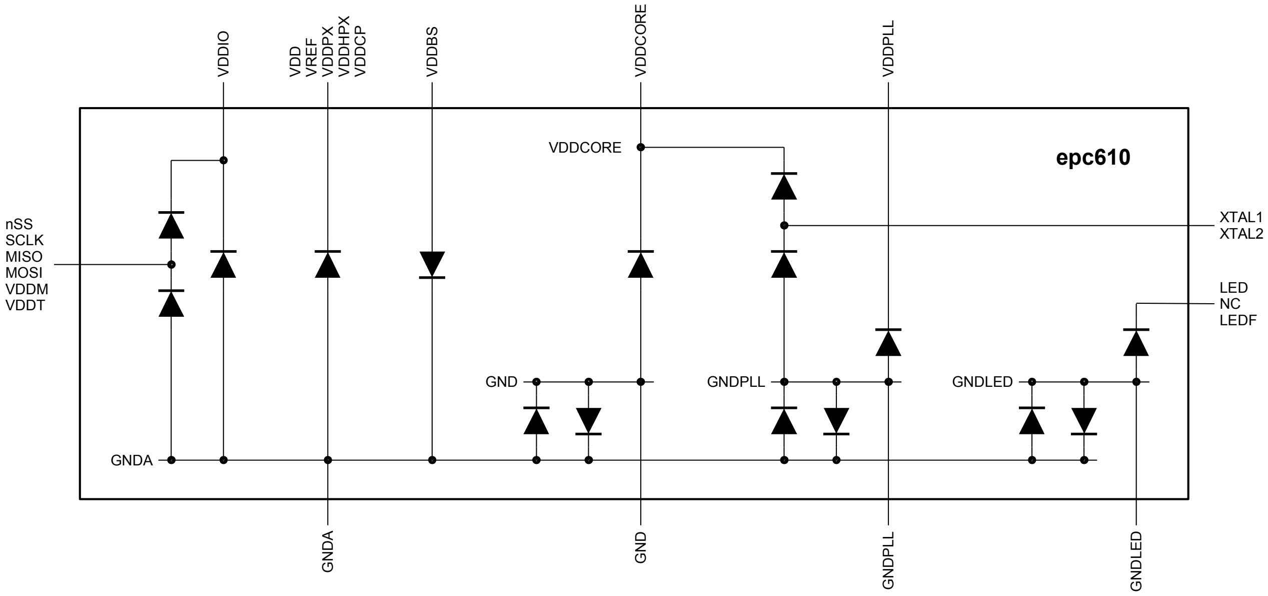

Figure 9: ESD protection of the pins

Reflow Solder Profile

For infrared or conventional soldering, the solder profile has to follow the recommendations of IPC/JEDEC J-STD020C (revision C and later) for lead-free assembly. The peak soldering temperature (T_L) should not exceed +260°C for a maximum of 4 sec.

Packaging Information (all measures in mm)

Tape & Reel Information

The devices are packaged into embossed tapes for automatic placement systems. The tape is wound on 178mm (7inch) or 330mm (13inch) reels and individually packaged for shipment. General tape-and-reel specification data are available in a separate datasheet and indicate the tape size for various package types. Further tape-and-reel specifications can be found in the Electronic Industries Association EIA-Standard 481-1, 481-2, 481-3.

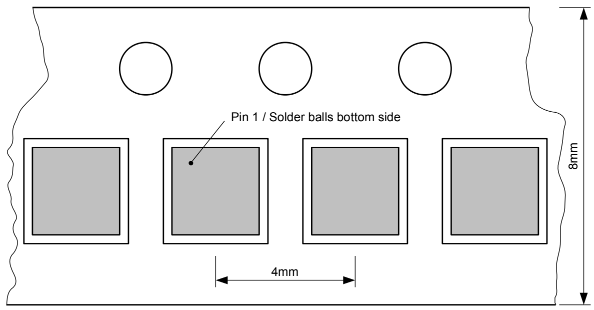

Figure 10: Tape dimensions

epc does not guarantee that there are no empty cavities in the tape. Thus the pick-and-place machine should check the presence of a chip during picking.

Ordering information

Part number	Part name	Package	RoHS compliance	Packaging method
P100 036	epc610-CSP24	CSP24	Yes	Reel

Table 5: Ordering information

Functional Description

This manual is arranged in the following sections:

■ Operation
This general description of the operation and the functionalities is targeted at the user and application level.

■ Hardware Design
All information regarding hardware design aspects are covered here.

■ Instruction Set
Contains a detailed description of the data communication and the command set.

■ Optical Design Considerations
The chapter where the user finds some design guidelines for developing appropriate optics and illumination for the device.

1. Operation

1.1. Introduction

The epc610 chip is based on the 3D-TOF principle. Modulated light is sent out by a transmitter. This light is then reflected by the object to be detected and the returning light is sampled by a photosensitive TOF CCD sensor. The receiver compares the phase difference between the emitted and the received light and computes the time difference of the “time-of-flight” individually per pixel. This value multiplied by the speed of light (ca. 300'000km/sec) and divided by 2 corresponds directly to the distance.

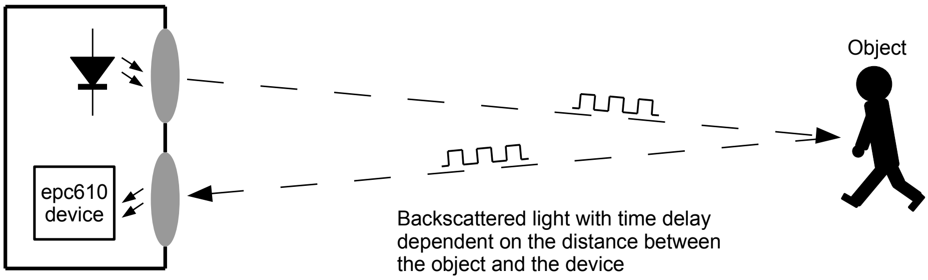

Figure 11: The time-of-flight principle

1.2. General overview

The epc610 chip is designed to enable simple and cost effective system designs. Together with a microprocessor and few external components, a fully functional TOF imager can be built (refer to Figure 12).

The epc610 system-on-chip contains:

■ A full data acquisition path with a power driver for the LED, the photo-receiver with 8x8 pixel TOF CCD array, the signal conditioning, the A/D converter and the signal processing.
■ An on-chip controller managing the data acquisition and the data communication.
■ An SPI interface for the command and data communication.
■ A supply-voltage power management unit.

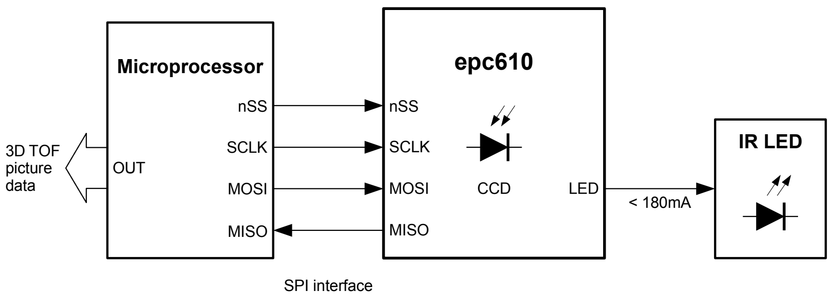

Figure 12: Basic application

The measurement functionality supports distance and ambient-light measurement with variable integration times, on-chip temperature measurement for drift compensation.

The sensitivity of the system can be adjusted on the fly to the object reflectivity, the object distance and the ambient-light conditions by means of integration time. The longer the integration time, the higher the sensitivity.
In cases where the illumination power of the built-in driver is not sufficient, the epc610 chip can also be used with an external LED driver. This allows longer operational ranges or faster measurements, resulting in a faster response time and reduced ambient-light sensitivity.

1.3. Operational mode

This chapter lists the available features for the epc610 device.

The 3D TOF camera works in combination with a microprocessor. It operates according a single shot principle. First, measurement type and integration time are set in the chip by sending commands from the microprocessor. Next, a command stimulates a sampling sequence of 4 samples (integrations or frames) for a complete measurement. Each time a integration cycle is finished and/or the next row of pixel data is loaded, data must be read via the SPI (refer to Figure 13). Out of the complete dataset, the microprocessor calculates the distance and the quality data (3D TOF image).

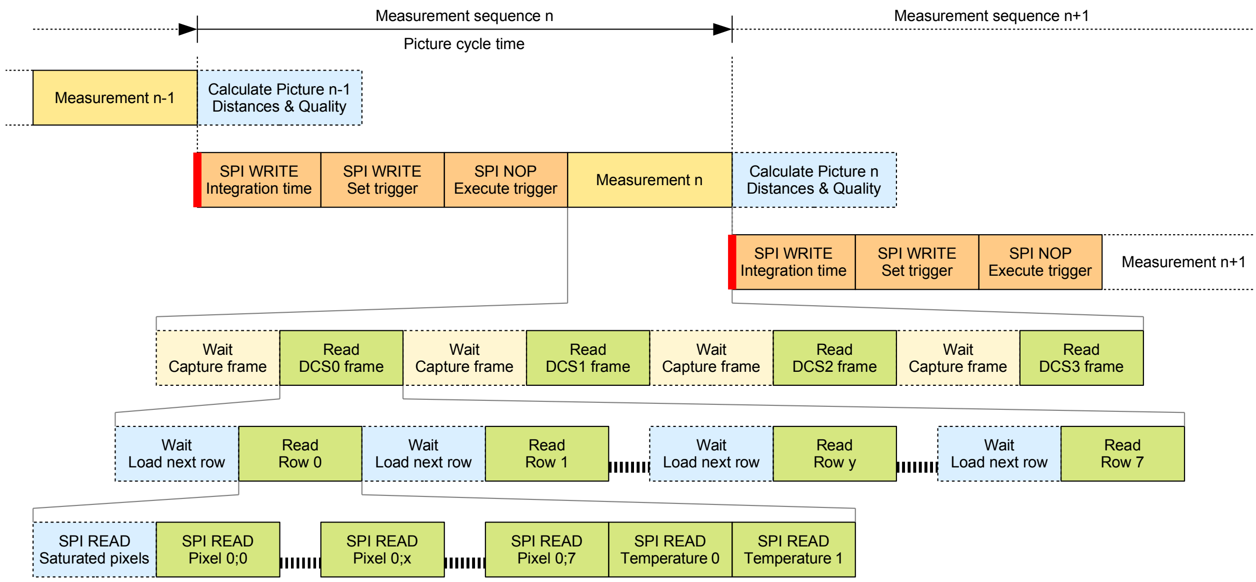

Figure 13: Basic distance measurement

The microprocessor controls the parameter setting for the measurement (the type and the time) and the start. It computes from the read-out data the final distance, the quality, the ambient-light and the temperature data. This also includes applying the necessary correction algorithms and to adapt the epc610 settings to the useful operational range and the present scenery conditions.

The epc610 chip supports 3D TOF imaging with an 8x8 pixel distance measurement, ambient-light measurement (similar to an optical power-meter or “Luxmeter”) and temperature metering.

1.3.1. Distance measurement

The distance measurement is done by single shots of 4 integration samples (frames). The distance picture is calculated from the measurement data of the 4 samples DCS0 – DCS3 (refer to Figure 14). The data read-out is per frame resp. per row. The distance and the quality per pixel are computed on the external microprocessor with the corresponding formulas for the values DCS0 – DCS3 of the frames.

Figure 13 shows the main procedure to catch the distance pictures. The calculation of the distance values follows the formula of Figure 14.

Distance calculation formula:

$$D[m] = \frac{c}{2} \cdot \frac{1}{2\pi f_{LED}} \cdot \left[\pi + \operatorname{atan}\left(\frac{DCS0 - DCS2}{DCS3 - DCS1}\right)\right] + D_{OFFSET}$$

D	Distance in meters
c	Speed of light e.g. 300'000'000m/s
f_{LED}	LED modulation frequency e.g. 10MHz
DCS0 - DCS3	Sampling amplitude
φ	Phase shift caused by the time-of-flight
D_{OFFSET}	Offset compensation, needs to be evaluated by calibration of each pixel.

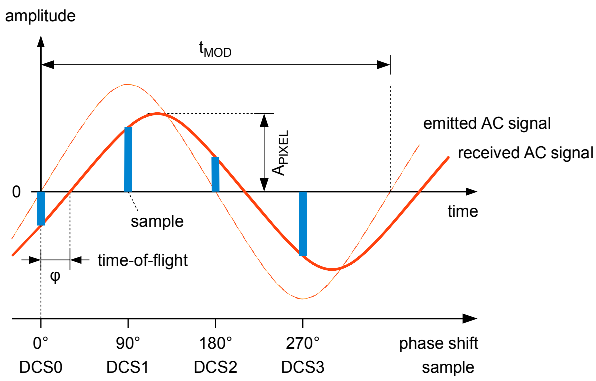

Figure 14: Sampling of the receiving waveform

Before the execution of a distance measurement, the type and the integration time need to be set by SPI commands. The acquisition sequence starts after the trigger command. Wait until the integration of a sample is finished and the next row is loaded before reading out the data row by row (refer to chapter 3.5.6: Command: READ Data). Once, the dataset of all samples DSC0 – DCS3 is read, compute the distance and the quality per pixel in regards to the necessary correction factors e.g. offset, ambient-light, temperature drift.

Notes:

- Once, the cycle has started, it cannot be terminated until the end. All of the data except the “Saturated pixels” must be read before the chip continues with the operation.
- Do not change the type or the time commands during the sequence as they are not ignored and change the corresponding mode on the fly (leading to data corruption).

1.3.2. Unambiguity range and integration time base

The epc610 3D TOF imager uses the time-of-flight principle. It is implemented with a repeating, continuous-mode modulation signal during the measurement phase (refer to Figure 15). Consequently, only signals returning within the maximum time slots can be detected unambiguously. This corresponds for the epc610 device to a maximum operating range of 15m @10MHz LED modulation frequency. Strongly reflected signals outside of this range may therefore interfere with the measurement.

The LED modulation frequency defines the unambiguity distance, the resolution of the distance signal and the time base for the integration time. It can be changed by the MOD_CLK_DIV value (refer to chapter 3.5.3.: Command: WRITE LED modulation clock) to adapt the chip to customer's application needs. Table 6 lists as an example some values of the LED modulation frequencies in function of the unambiguity distance, of the distance resolution and for the corresponding divider of the LED clock.

LED modulation frequency	Unambiguity distance	Distance resolution [1]	LED clock divider	MOD_CLK_DIV [2]	Integration time [3]
20 MHz	7.5 m	0.25 cm	1	0	divided by 2
10 MHz	15 m	0.50 cm	2	1	as per chapter 3.5.1.
5 MHz	30 m	1.00 cm	4	3	multiplied by 2
2.5 MHz	60 m	2.00 cm	8	7	multiplied by 4
1.25 MHz	120 m	4.00 cm	16	15	multiplied by 8

Table 6: LED modulation frequencies vs. unambiguity distance and integration time

[1] Distance resolution for an typical output range e.g. 0 - 3'000d
[2] Refer to chapter 3.5.3.: Command: WRITE LED modulation clock.
[2] Refer to chapter 3.5.1.: Command: WRITE Integration time.

The result is only uniquely defined below the unambiguity distance. It is the limit of the maximum operational distance.

1.3.3. Sensitivity, integration time and operating range

The operational range of the complete system is limited by the sensitivity of the receiver as well as by the illumination power emitted by the modulating light source (e.g. LED) for distances below the unambiguity distance.

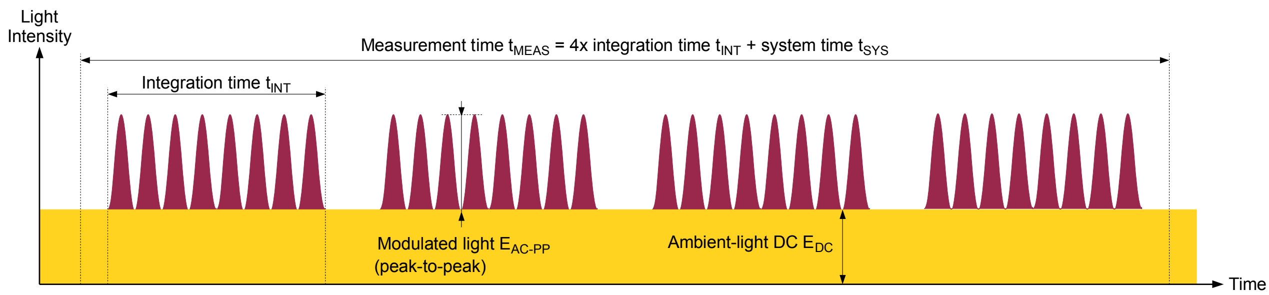

Figure 15: The light detected by the receiver

The system sensitivity consists of two factors: The hardware sensitivity S_{AC} of the photosensor (refer to chapter: Timing and optical Characteristics) and the exposure time (integration time t_{INT}).

The measurement evaluation is done by computing the distance out of 4 samples received in one measurement cycle t_{MEAS}. A sample is the collected power of the receiving light signal during the integration time t_{INT} (refer to E_{AC} in Figure 15). This means the sensitivity corresponds to the integration time: The longer the integration time, the more sensitive the measurement.

The measured irradiance E_{AC} (uncalibrated) at the surface of a pixel can be calculate out of the AC sensitivity S_{AC}, the used integration time t_{INT-AC}, the reference integration time $t_{INT-REF-AC}$ and the amplitude A_{AC} of the received modulated signal (refer to chapter 1.3.5. Quality of the measurement result) in the following way:

$$E_{AC} = S_{AC} \cdot \frac{t_{INT-REF-AC}}{t_{INT-AC}} \cdot A_{AC} \qquad \text{e.g.} \quad E_{AC} = 31 \frac{nW/cm^2}{LSB} \cdot \frac{103\,\mu s}{205\,\mu s} \cdot 1'000\ LSB = 16\,\mu W/cm^2$$

Illumination power, remission of the object (reflectivity), sensitivity of the sensor together with the integration time are limiting the distance operational range. For more detailed information, refer to epc's application note: AN02 Reflected power calculation.

It will probably not be possible to cover the full operational range within one integration time step due to the dynamic range of the receiver's electronics. The possibilities to extend the operating range or to influence the response time are:

- to adapt the integration time correspondingly to the necessary sensitivity as demonstrated in Figure 16.

- or alternatively: use an additional, external LED driver to adjust the illumination to the needed system sensitivity level (refer to chapter 1.3.10.: Extended operating range).

The easiest way is to adapt the exposure time to the current illumination situation (e.g. in Figure 16). With the command formats, which allows adjusting of the exposure time, it is easy to do. It is simple to change the exposure time on the fly: an “INTEGRATION” command can be sent to the chip before a capture is initiated.

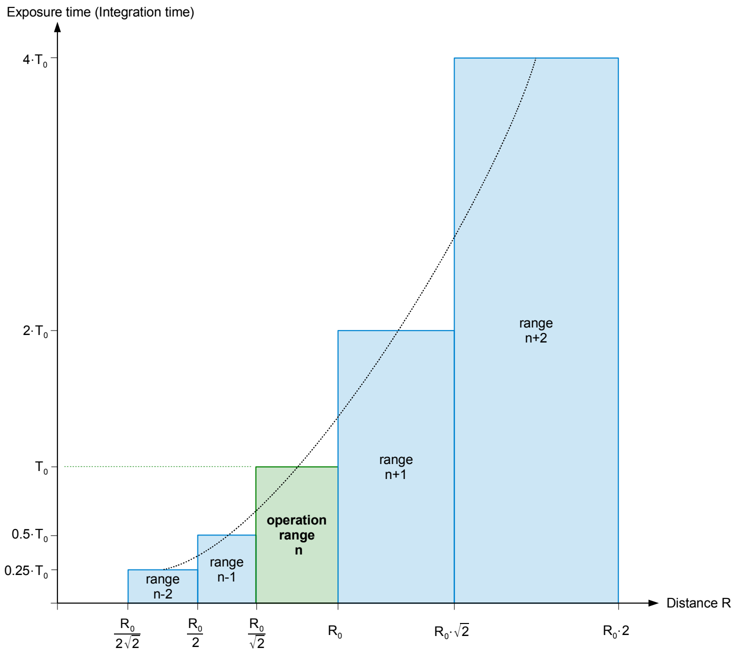

Figure 16: Operating ranges as a function of distance and exposure time based on doubling the light power to the sensor

1.3.4. Ambient-light suppression

An important function of the range-finder is the ability to separate the self-emitted and reflected modulated light E_{AC} from the ambient light E_{DC} (refer to Figure 15). The built-in ambient-light suppression E_{Sup} removes the DC or low frequent signal distortions, caused by foreign light sources e.g. sunlight, daylight, room illumination, etc., from the measuring signal. The user has not to take care of this, it is done by the chip automatically. To see the capability of this function, refer to Table 3 for example values as a function of the wavelength and compared to sunlight.

Similar to the system's sensitivity of the modulated light, is the ambient-light suppression a function of the integration time. The longer the integration time, the more the measurement becomes sensitive to the ambient-light.

Notes:

- The ambient-light suppression of the chip must not be confused ambient-light measurement command. It is a fixed built-in functionality, which is removing the DC light component from the AC measurement signal only.
- A DC or AC photo-signal can be generated by ambient-light (e.g. sunlight) or by cross-talk from the IR-LEDs. However, if this is above the stated maximum value, then the sensor or the input electronics are saturated. This blocks the detection of the AC modulation signal.

1.3.5. Quality of the measurement result

The epc610 provides information on the quality and the validity of the received optical signal. This reflects the confidence level of the measurement result. The better the received signal, the better and more precise the distance measurement will be.

Each distance measurement of every pixel has its own validity and quality.

The primary quality indicator for the measured distance data is the **amplitude value of the received modulated light A_{AC}**.
After each measurement this needs to be calculated from the DCSx values delivered by the chip. This amplitude value is the **feedback parameter that is used to set the integration time for the next measurement**.

$$A_{PIXEL-AC} = \sqrt{\frac{(DCS0-DCS2)^2}{4} + \frac{(DCS1-DCS3)^2}{4}}$$

Quality indicator:	**Weak illumination: e.g. A_{AC} < 50 LSB**	
Status & reason:	The signal has a reduced accuracy, because it is above, but close to the noise level.	
Action:	Increase integration time for the next measurement	

Quality indicator:	**Sufficient illumination: e.g. 50 LSB < A_{AC} < 100 LSB**
Status & reason:	The signal quality and the accuracy is sufficient and not close to any limits. Noise level may be increased.
Action:	No action necessary. See note below

Quality indicator:	**Excellent illumination: e.g. 100 LSB < A_{AC} < 1'000 LSB**
Status & reason:	The signal quality and the accuracy is excellent and not close to any limits.
Action:	No action necessary. See note below

Quality indicator:	**Too bright illumination: e.g. 1'000 LSB < A_{AC}**
Status & reason:	The signal is close to or above the limit of too much light (maximum signal limit).
Action:	Decrease integration time for the next measurement. See note below

Note:
Generally, the higher the received signal, the better and more precise the distance measurement will be. However, it is good practice to control the integration time such that an amplitude value between 100 ... 200 LSB is achieved. Higher values will only slow down the acquisition rate due to longer integration times, but are not significantly improving signal to noise ratio.

The quality indicator for the ambient-light measurement is the **ambient-light amplitude A_{DC}**.
The rules to apply are the same as for the modulated light amplitude.

The quality indicator for the distance noise is the ratio AMR of ambient-light to the modulated light. This value may be calculated and used additionally to the above amplitude value if the respective application is subject to intense ambient light.

Quality indicator: **Ratio AMR of ambient-light to modulated light**

$$AMR[dB] = 20 \cdot \log\left(\frac{E_{DC}}{E_{AC}}\right) \qquad \text{e.g.} \quad AMR[dB] = 20 \cdot \log\left(\frac{792\mu W/cm^2}{16\mu W/cm^2}\right) = 34dB$$

Refer for E_{DC} to chapter 1.3.6. Ambient-light measurement (optical power-meter) and for E_{AC} to chapter 1.3.3. Sensitivity, integration time and operating range.

Status & reason: This ratio is one of the influencing factors regarding the distance noise (refer to Table 2, section Distance noise)

Action:	< 60 dB: excellent	No action necessary.
	< 70 dB: sufficient	Is a lower noise level needed, do the next measurement with a longer integration time or an increased illumination power.
	> 70 dB: weak	Do the next measurement with a longer integration time or an increased illumination power.

There are also validity indicators delivered by the chip after a measurement. These will help to detect saturated pixels as a result of too much illumination or too long integration time.

Validity indicator:	**Status "Saturation" of a pixel is set for one ore more of the DCSx values.** Refer to chapter 3.5.5.: Command: READ Saturated pixels
Status:	The pixel receives too much light.
Reason:	Fault conditions: - Too much modulated light-signal or too reflective object. - Too much ambient-light.
Action:	Dump data and repeat the measurement with a decreased integration time or measure the ambient-light.

Validity indicator:	**Maximum signal limit: one or more of the DCSx values per pixel ≥ 1'000 LSB**
Status:	Suggests there is an object, but it is out of the usable operating range.
Reason:	Fault conditions: - The object is too reflective. - It is too close to the sensor. - There is too bright illumination or too much modulation signal is emitted.
Action:	Dump data and repeat the measurement with a decreased integration time.

Validity indicator:	**Noise level limit: All DCSx values per pixel ≤ 50 LSB**
Status:	There is a lack of signal or no usable receiver signal. The received signal is in the noise level. The accuracy of the distance calculation is out of tolerance.
Reason:	Regular operation: - Absence of an object in the operating range. Fault conditions: - The object has too little remission (reflectivity). - It is too far away. - The illumination is too dim. Too little modulation signal is emitted.
Action:	Dump data and repeat the measurement with an increased integration time.

Table 7 shows a quality decision matrix as a summary of the validity and quality parameters for the distance measurement.

Step	Sensor status	Status saturated	Maximum signal	Noise level	Modulated light amplitude A_{AC}	Ambient to modulated light AMR	Action
1	Saturation or bright object within scene	yes					Repeat measurement with decreased integration time and/or illumination
2	Saturation or bright object within scene	no	above				Repeat measurement with decreased integration time and/or illumination
4	No object detected	no	below	below			Repeat measurement with increased integration time or illumination
3	Over-exposure or bright object within scene	no	below	above	> 1'000 LSB		Repeat measurement with decreased integration time or illumination
4	No object detected	no	below	above	< 50 LSB		Repeat measurement with increased integration time or illumination
5	Too much ambient-light	no	below	above	50 LSB … 1'000 LSB	> 60 db (or > 70 dB)	Repeat measurement with increased integration time or illumination
6	Object detected	no	below	above	Excellent: 100 … 1'000 LSB Sufficient 50 … 100 LSB	< 60 db (or < 70 dB)	No action necessary

Table 7: Quality decision matrix (per pixel)

1.3.6. Ambient-light measurement (optical power-meter)

Instead of getting distance data, the epc610 chip can measure the ambient-light level per pixel. Features of this powerful function are:

- Watching the ambient-light level during the distance measurement to prevent faulty conditions or to use the information for compensation reasons.
- Use the ecp610 as an optical power-meter e.g. for brightness control.
- or in combination of both: e.g. everywhere where there is a presence or an absence of an object, the illumination needs to be controlled.
- Grayscale imaging.

The measured irradiance E_{DC} (uncalibrated) of the received ambient-light at the pixel surface can be calculate out of the DC sensitivity S_{DC}, the used integration time t_{INT-DC}, the reference integration time $t_{INT-REF-DC}$ and the amplitude A_{DC} of the received ambient-light in the following way:

$$E_{DC} = S_{DC} \cdot \frac{t_{INT-REF-DC}}{t_{INT-DC}} \cdot A_{DC} \qquad \text{e.g.} \quad E_{DC} = 12.3 \frac{nW/cm^2}{LSB} \cdot \frac{103\mu s}{1.6\mu s} \cdot 1'000\ LSB = 792\mu W/cm^2$$

For the distance measurements, it is not necessary to do the ambient-light measurement all the time. Usually, the ambient-light conditions are changing slowly. It makes sense to do it as a control, in order to have enough detection margin in the receiver electronics or if the quality is indicating a faulty measure.

Notes:

- The quality indicator for the ambient-light measurement is the ambient-light amplitude A_{DC}. The rules to apply are the same as for the modulated light amplitude.
- The ambient-light measurement is a metering functionality only, which can be used for distance correction or ambient-light reading. It is completely independent of the chip internal ambient-light suppression function that eliminates DC light components from the measurement signal (refer to chapter 1.3.4. Ambient-light suppression).
- Take care that the ambient-light measurement follows the same procedure of Figure 13. This means that all 4 frames must be mandatorily read. The result is: 4 similar, time sequential, black& white pictures.

1.3.7. Temperature metering

Two on-chip temperature sensors at the opposite sides of the pixel field give back uncalibrated temperature readings. The readings of each row also contain the two temperature values.

- This allows the compensation of the signal drifts caused by changing thermal conditions in the light source and the sensor.
- If the user does his own calibration (e.g. °C or F), he can use it as a temperature sensor too.

1.3.8. Measurement sequence

Using all the features of the epc610 device in combination, a basic possible measurement flow is given in Figure 17:

- ■ Execute a distance measurement and check the validity and quality of the signals. If an action is needed, do it accordingly.
- ■ If the camera operates in an ambient-light changing condition, occasionally read the ambient-light for quality check and compensation.
- ■ If the camera operates in thermally changing conditions, occasionally use the temperature reading for compensation. Other than on the epc600 TOF imager, the temperature value will be delivered with each measurement data sequence automatically
- ■ Calculate, based on the correction data, the final distance value – or whatever is needed.

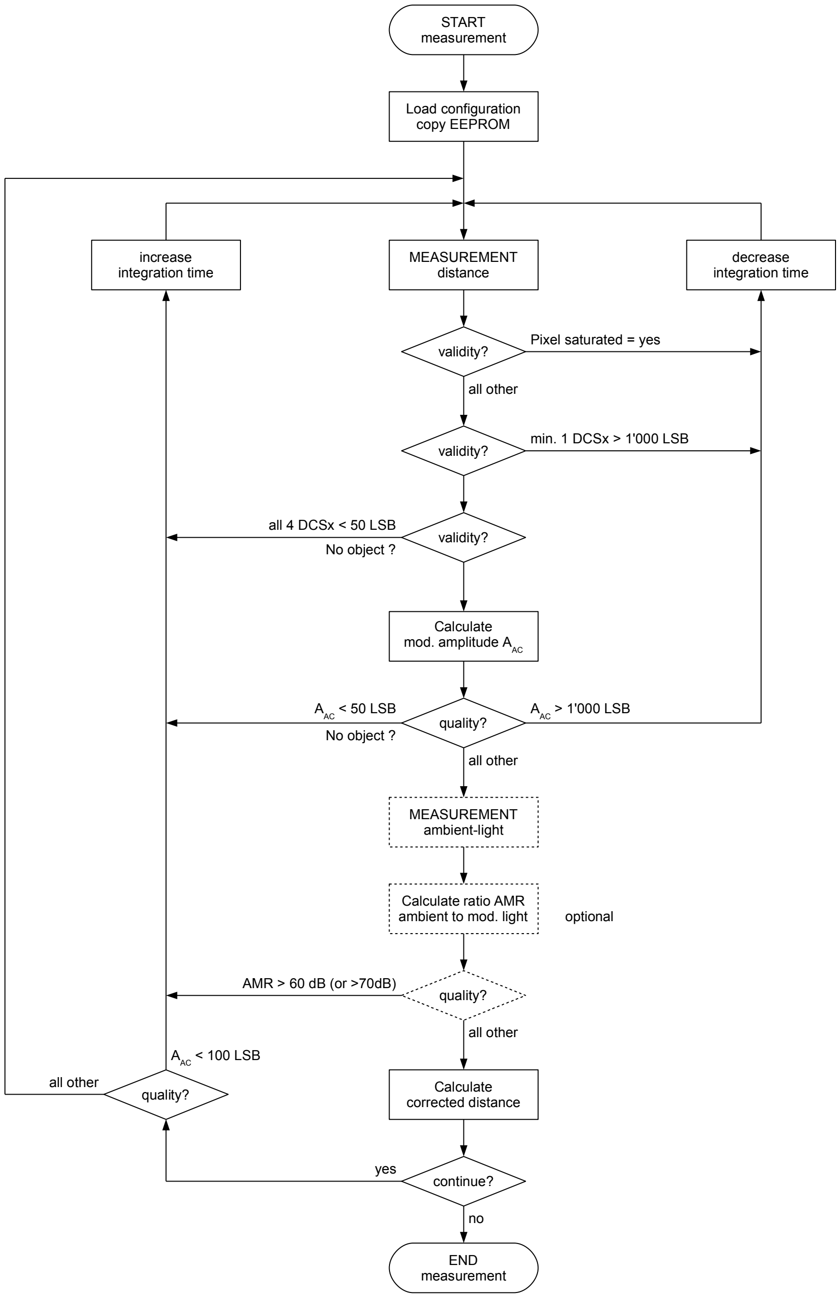

Figure 17: Principle measurement flow per pixel

This flow is not only for detecting objects: It is also possible to observe and track the object (once captured).

1.3.9. Calibration and compensations

Due to the fact that the 3D TOF camera chip does not know its surrounding environment and the phase-shifts caused by the electronic implementation and also due to manufacturing tolerances, a calibration of the sensor is necessary.

The complexity and magnitude of compensation and calibration measures is dependent on the application.

Influencing variables for various attributes are:

- Distance: Offset, Slope scaling, Linearity, Reflectivity, Ambient-light, Integration time, Temperature.
- Reflectivity of the object: Quality, Ambient-light.
- Ambient-light: Offset, Slope scaling, Linearity, Integration time, Temperature.
- Temperature: Offset, Slope scaling, Linearity.

These compensations are necessary for the microprocessor to correct the raw distance data in the final measurement.

Fix pattern noise

The pixels of the imager will not behave evenly due to manufacturing tolerances. This effect can be reduced to a minimum by a calibration and correction of each pixel itself. It is suggested to perform all corrections for each pixel individually.

High dynamic rang within as scene

Not all pixels in a picture are usually well illuminated and have an excellent amplitude. This may specifically be the case in scenes with objects at different distances, which causes variable illumination conditions. For such scenes it is suggested to perform multiple measurements with varying integration times and to use only the well illuminated pixels from each shot.

Averaging of data

Distance data need to be averaged only on final corrected values, not on DCSx level. Otherwise the result will be erroneous.

DCSx pixel data can be averaged inside of a DCSx frame for pixel reduction.

1.3.10. Extended operating range

The epc610 device is a 3D TOF camera designed as a system-on-chip for minimum part count circuits. Therefore, a LED driver is integrated on-chip.

In cases where the illumination achieved with the built-in driver is not sufficient to detect near and far objects in the expected operational range or in the necessary response time, the epc610 chip can be used with a more powerful external LED driver (refer to chapter 2.5. External LED driver).

1.3.11. Multi 3D TOF camera application

3D TOF cameras are not always operating in a single sensor application. In some applications, more than one sensor is deployed to partially or entirely cover the same observation field. The epc610 3D TOF camera uses signal-processing based on the sinusoidal modulation theory of the time-of-flight principle.The LEDs are modulated with 10MHz square-wave and a duty cycle of 1:1. There is no coding in the modulation signal to make each device unique. To date, in multi 3D TOF camera applications, cross-talk between the signals of closely placed individual sensors can occur.

The single shot principle of the epc610 chip allows an easy synchronization of multiple sensors by a fixed time synchronization between imager devices (sequencing of sensors).

2. Hardware Design

2.1. What performance can be achieved?

A typical example of an application is a very small 3D TOF camera (refer to Figure 20).

Figure 18: Low power, high performance 3D TOF imager
Size: 32 x 22 x 25 mm

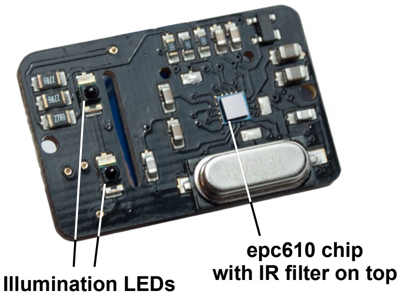

Figure 19: Chip on PCB board

In this example, a range of up to 2.4m can be expected on white targets when using: two SFH4059 LEDs directly driven by the LED pin, a receiver lens of ø3.6mm with a focal length of f = 2.8mm (aperture angle of 4.9° x 4.9°) and an integration time t_{int} of 1.64ms.

The maximum measurement cycle time in this application is: $t_{MEAS} = 4 \cdot t_{INT} + 1.73ms = 8.29ms$
(refer to chapter 3.5.9. Cycle time calculation).

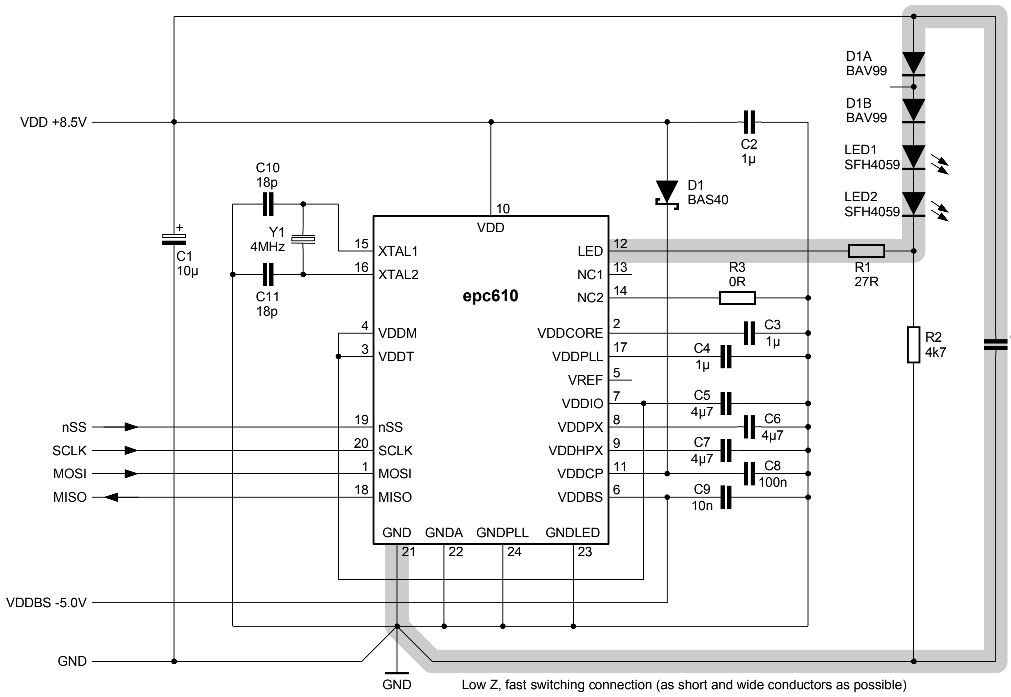

Figure 20: Minimum part count application

2.2. General Hardware Configuration

The general hardware configuration section covers all design aspects for an epc610 circuit.

2.3. Power Supply and Clock generation

The external voltage supplies are +8.5V DC as a main supply and -5.0V DC as a bias voltage. Both supplies need to be well regulated and with a low level of noise and ripple voltage (because the epc610 chip is a sensitive, highly amplifying device).

All other necessary voltages are generated on-chip. The internally generated voltage levels V_{SC} (see Table 4) have to be taken into consideration in order to choose the right components for the design.

All necessary power supply decouplings and the supply of the external reference clock have to be designed according to Figure 21 and Table 8. Capacitors C3 – C9 are used for decoupling of the internally generated voltages.

The Schottky diode D1 is vital to ensure a correct power-up of the device.

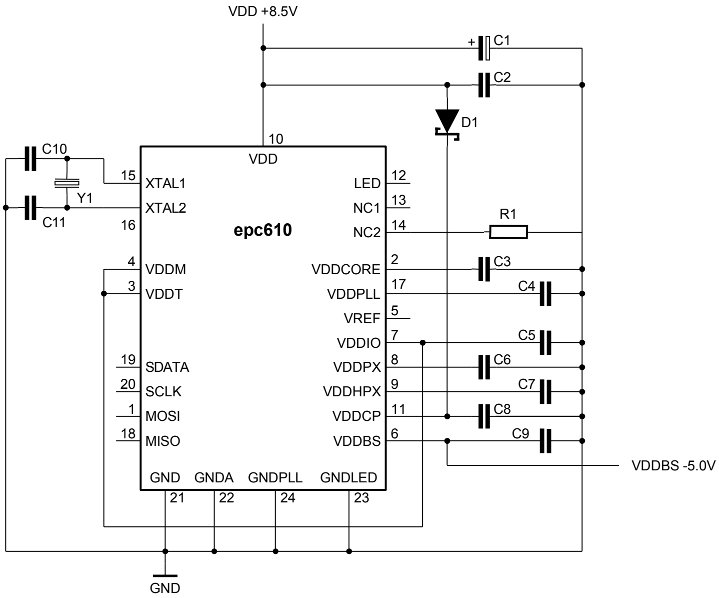

Figure 21: Main power supply decoupling and clock supply

Part No.	Pin	Pin No.	Component value				
			Min.	Nom.	Max.	V_{SC}	Type
C1	VDD	10		10µF		+8.5V	
C2	VDD	10		1µF		+8.5V	Ceramic X7R
C3	VDDCORE	2	1µF	1µF	3.3µF	+1.8V	Ceramic X7R
C4	VDDPLL	17	1µF	1µF	3.3µF	+1.8V	Ceramic X7R
C5	VDDIO	7	3.3µF	4.7µF	10µF	+5.0V	Ceramic X7R
C6	VDDPX	8	3.3µF	4.7µF	10µF	+5.0V	Ceramic X7R
C7	VDDHPX	9	3.3µF	4.7µF	6.8µF	+10V	Ceramic X7R
C8	VDDCP	11	10nF	100nF	100nF	+12V	Ceramic X7R
C9	VDDBS	6	10nF	10nF	20nF	-5.0V	Ceramic X7R
C10	XTAL1	15	See note 2			+1.8V	Ceramic NP0
C11	XTAL2	16	See note 2			+1.8V	Ceramic NP0
Y1	XTAL1 & XTAL2	15 & 16		4 MHz			Crystal-oscillator
D1	VDD & VDDCP	10 & 11					Schottky diode
R1	NC2	14		zero Ohm		+5.0V	Resistor

Table 8: Component values

Notes:

1) Leave open the pins NC1 and VREF. They do not require any termination.

2) Refer to the datasheet of the crystal-oscillator e.g. typ. 18pF.

2.4. On-chip LED driver

A feature for the minimum part count system is the on-chip LED driver. Figure 22, Figure 23 & Figure 24 show examples for possible circuitries. The design has to take in consideration that these LEDs are switched very fast (e.g. 10MHz) and with high power (<180mA). Suggested are high speed LEDs with short switching times e.g. Osram SFH4059, Vishay VSMB2000, Stanley DNK5306. The layout needs to be well decoupled and with low Z conductors.

Notes:

- Take care that the voltages at LED and LEDF do not exceed their specified operating range of maximum +5V.
- The signal processing of the epc610 chip is based on a sine-wave modulated light-signal. All descriptions in this manual are related to this. However, to simplify the LED driver circuit as well to reduce the power-losses of the LED, the chip uses a square-wave modulated signal for the LED. This change together with all the other non-linear influences on the signal path leads to only a small error, which can easily be corrected in the measurement data (refer to chapter 1.3.9.: Calibration and compensations).

LEDs with a +5V supply

If a +5V supply is available, the LEDs can simply be supplied by this as shown in Figure 22. Resistor R1 limits the LED current <180mA.

For the LED power dissipation calculation, refer to chapter 3.5.9. Cycle time calculation.

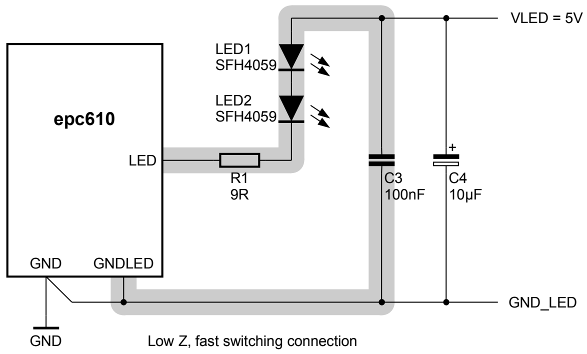

Figure 22: Short range application
with +5Vdecoupled LED supply

Short range application design (LED supply from 8.5V)

The circuit Figure 23 drives two power IR LEDs. The output LED is driven by an open drain switching transistor. The illumination intensity of the LEDs is defined by the current flowing through the resistor R1. For the output LED = on, the current of the resistor R1 is <180mA. In order to have safe voltage operating conditions for the output LED (+5.0V), there is a minimum current of <1mA flowing through the LED diodes and the D1 diodes in the off-state. This also gives the advantage of an enhanced switching performance for the LEDs. This off-current is set by the resistor R2. C3 and C4 are the charge capacitors to supply the LEDs. In order to support the required fast switching, C3 shall be of a ceramic type. The decoupling of the supply of the epc610 chip is done by C1 and C2 (ceramic type). The resistor R3 decouples the LED feeding circuit from the ep610 supply. The voltage drop of the diodes D1A and D1B adjust the voltage supply level to the LED supply level. The advantage of this concept is that it gives a good decoupling between the epc610- and the LED-supply.

For the LED power dissipation calculation, refer to chapter 3.5.9.: Cycle time calculation.

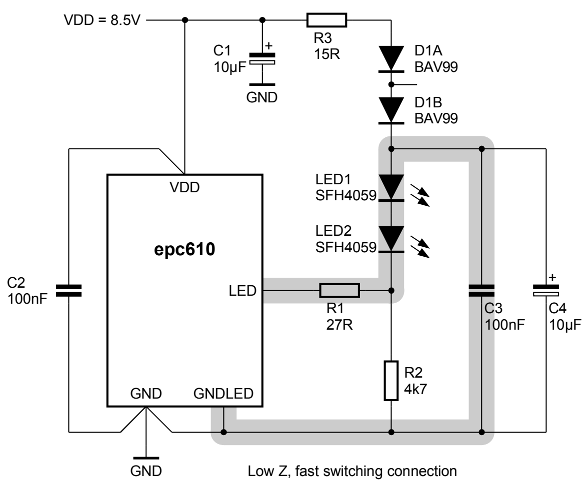

Figure 23: Short range application
with a decoupled LED supply

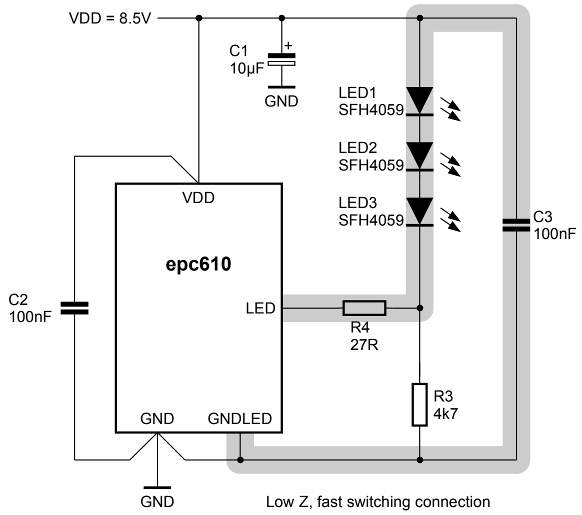

Figure 24: Mid range application
with a minimum part count circuit

Mid range application design (LED supply from +8.5V)

The circuit of Figure 24 is a minimum part count design for a more powerful illumination (3 LEDs are equal to 50% more illumination energy).

The design considerations are exactly the same as before. The difference is the additional third LED3, which replaces the diodes D1A and D1B, in order to have more powerful illumination. As it is used as a minimum part count design, the decoupling between the LED supply circuit and the epc610 supply is not of the same quality as in the short range example before. Therefore, the layout design regarding the noise and ripple voltage has to be done very carefully.

2.5. External LED driver

For a more powerful, sensitive or fast system application with an epc610 chip, the use of an external LED driver is an option. The design has to take into consideration that the LEDs are modulated at high frequencies (e.g. 10MHz) and with high power. So far, the layout needs to be well decoupled and with low Z conductors. The schematic has to follow the correct signal inversions as given in Figure 25. This is important in order to have the correct phase for the modulation.

Note: Take care that the voltage at pin LED do not exceed the specified operational range of maximum +5V.

epc610's pin LED is driven by an open drain switching transistor. The pull-up termination resistor R1 tied to the V_LOGIC supply (+5V) guarantees safe voltage operating conditions for the output LED. The modulation signal of output LED feeds a fast inverting digital buffer IC1. It drives the fast switching transistor T1. T1 switches the current through LED1-LEDn on/off in order to modulate the light. Output LED = low corresponds to light = on.

As opposed to the on-chip driver, such a design can have additional light levels as the circuit in Figure 25 shows. An I/O port of the microprocessor switches the intensity to the LOW or HIGH level. IC1 and IC2 are the necessary selecting logics to drive the transistors T1 and T2. The illumination (current through LED1-LEDn) is controlled by R2 and R3 for the high and the low illumination level.

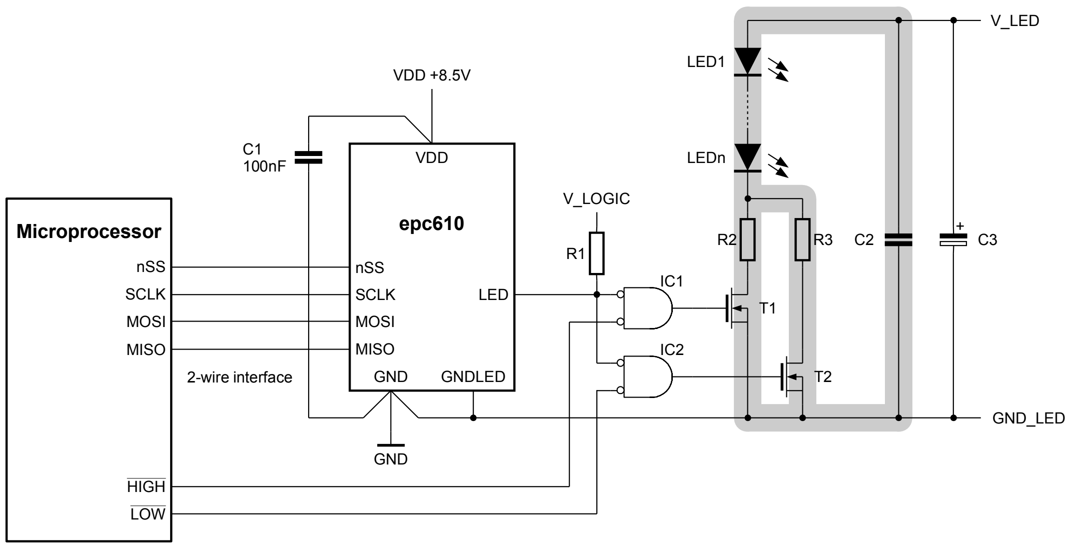

Figure 25: Long range or fast response application (principal schematic)

Advantages of this circuit are: the free design of the illumination power (number of LEDs), the additional selectable light levels for extending the operational range, the independent voltage supply for the LEDs and the strong decoupling of the epc610 supply and LED circuitry.

3. Instruction Set

The SPI interface allows the user to communicate with the epc610 chip. The graph of the principle communication flow is in Figure 13.

Starting a measurement, reading the result and setting the correct user parameters for operation are the main functions. All configurations are set at run-time, are loaded immediately and are not stored in the chip.

The user can adapt the epc610 chip to his needs and application. For this reasons, the device has a SPI interface and a built-in memory for the corresponding parametrization.

- Sets operating parameters.
- Triggers the measurement sequence.
- Provides data access by a read function.
- Allows reloading of the factory configuration.

All these functionalities are described in detail in chapter 3.4.: Start-up / load Parameter and configuration memory.

3.1. SPI interface

How the hardware needs be connected is shown in the schematic of Figure 26.

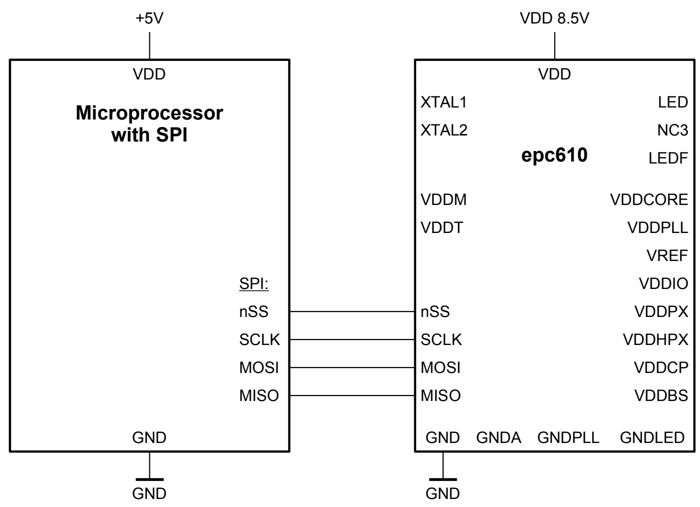

Figure 26: Schematic of the SPI connection

The interface is for single slave use. It is targeted to operate up to a 10MHz clock frequency. While data is sent from the microprocessor to the epc610 chip, the result of the last (or more generally of the previous command) is sent back according the SPI protocol in Figure 28.

One complete SPI frame consists of 16 bits (Word access), split into:

- 2 bit command ID (CID) or response ID (RID)
- 6 bit read or write address
- 8 bit data

The timing of the SPI frame is shown in in Figure 27 and of the SPI hardware bus Figure 28 . At the target SPI frequency of 10MHz, the access time for one SPI frame is <1.7µs.

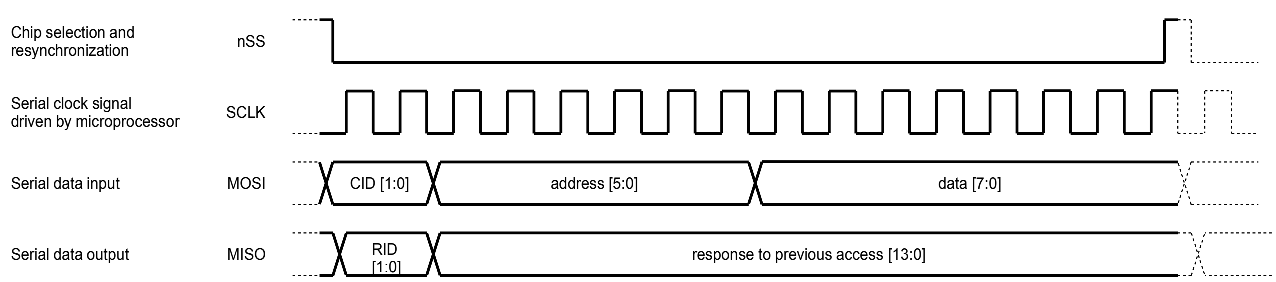

Figure 27: SPI frame 16 bit

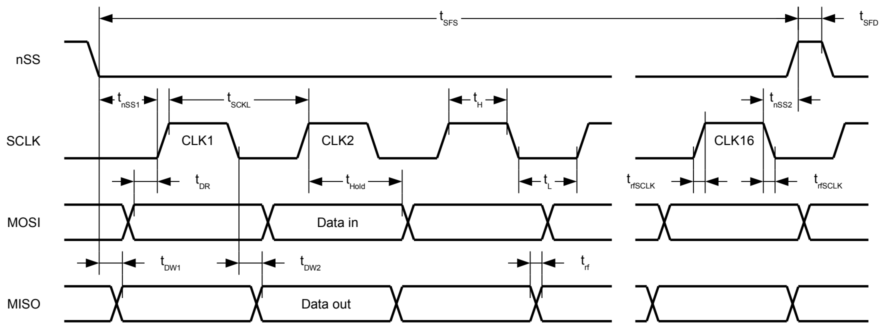

Figure 28: SPI bus timing

Symbol	Parameter	Min.	Typ.	Max.	Unit
nSS	SPI slave selection				
SCLK	SPI serial clock				
MOSI	SPI serial data input				
MISO	SPI serial data output; no tri-state output; only for single user systems				
t_{SFS}	Slave selection time for 1 complete data frame (Word access)	15.2*t_{SCLK}			
t_{SFD}	Slave deselection time for the data frame synchronization	10			ns
f_{SCLK}	Clock frequency of SCKL			10	MHz
t_{nSS1}	Set-up time for the first rising edge of SCKL after the falling edge of nSS	15			ns
t_{nSS2}	Set-up time for the rising edge of nSS after the rising edge of clock 16	15			ns
t_{SCLK}	Cycle time of SCKL = 1/f_{SCLK}	100			ns
t_H / t_L	HIGH and LOW period of SCKL	15			ns
t_{rfSCLK}	Rise or fall time for the signal SCKL			10	ns
t_{DR1}	Set-up time for the first rising edge of SCKL after the falling edge of nSS	15			ns
t_{DR}	Input data set-up time of MOSI before the rising edge of SCKL	15			ns
t_{Hold}	Input data hold time of MOSI	15			ns
t_{DW1}	Output data of MISO valid after the falling edge of nSS			15	ns
t_{DW2}	Output data of MISO valid after the falling edge of SCKL			15	ns
t_{rf}	Rise or fall time for the signals MOSI and MISO			20	ns

Table 9: SPI signal and timing definition

3.2. SPI commands and responses

CID [1:0]	Address / Data	Command	Operation / Usage
00	00'0000'0000'0000	NOP 0x0000	No operation - can be used for polling, if the microprocessor waits for a re-sponse from the SPI slave
01	aa'aaaa'0000'0000	READ	Reads data from the requested address of the SPI slave aa'aaaa 6 bit read address [5:0]]
10	aa'aaaa'dddd'dddd	WRITE	Writes data to the requested address of the SPI slave aa'aaaa 6 bit write address [5:0] dddd'dddd 8 bit write data [7:0]
11	00'0000'0000'0000	QUIT 0xC000	Quit operation – stops all activities of the SPI interface, which might be still in progress

RID [1:0]	Address / Data	Response	Operation / Usage
00	00'0000'0000'0000	IDLE 0x0000	The SPI slave is in the idle state; no pending transactions. Action: Proceed with processing
00	11'0011'0011'0011	READ_NOTDONE 0x3333	The previous READ command is not yet finished Action: - Send NOP until device answers with IDLE. - Proceed with processing. 1. Failure case: Chip answers forever with READ_NOTDONE Action: - Send QUIT until device answers with QUIT_RESPONSE. - Try to repeat last READ operation again 2. Failure case: Hardware or clock signal inputs e.g. of the oscillator: Chip answers forever with READ_NOTDONE. Check hardware or communi-cation. Remark: Unless a QUIT command is sent (abort of current command), this response is received for the SPI operation in progress.
01	aa'aaaa'dddd'dddd	READ_DONE	Returns the read data aa'aaaa 6 bit read address [5:0] dddd'dddd 8 bit read data [7:0]
10	aa'aaaa'dddd'dddd	WRITE_RESPONSE	WRITE command received and the write-cycle started aa'aaaa 6 bit write address [5:0] dddd'dddd 8 bit write data [7:0]
11	00'1100'1100'1100	BUSY 0xCCCC	The SPI is executing a WRITE command. Action: - Send NOP until device answers with IDLE (e.g. Reload factory setting of the EEPROM). - Proceed with processing. 1. Failure case: Chip answers after WRITE command forever with BUSY Action: - Send QUIT until device answers with QUIT_RESPONSE. - Try to repeat last WRITE operation again. 2. Failure case: Hardware or clock signal inputs e.g. of the oscillator: Chip answers forever with BUSY. Check hardware or communication. Remark: Unless a QUIT command is sent (abort of current command), this response is received for the SPI operation in progress.
11	10'0011'1000'1110	QUIT_RESPONSE 0xE38E	Response of the QUIT command; stops all activities of the SPI interface. Action: - If a QUIT was sent in an ERROR condition, follow the ERROR procedure as described in section ERROR. - otherwise, proceed with processing
11	11'1111'1111'1111	ERROR 0xFFFF	An error occurred on the SPI bus or the SPI protocol. Action: Is depending of the running task a) during regular READ/WRITE operation: - Repeat the command (second last), which got as a replay the ERROR message. b) during command sequence READ DATA (during the readout process of the DCSx measurement): - The actual measurement data is not valid anymore longer. - Follow the ERROR handling procedure for a lost synchroni-zation described in the command READ DATA (Readout and scrap data until the read data remains 0 for all the time). - Continue with a new measurement as usual.

Table 10: SPI commands and responses

To allow the correct operation of the on-chip synchronization and of the error detection, the SPI nSS signal needs to be de-asserted and re-asserted between two consecutive SPI frames. This inter-frame gap can be as short as defined in Table 9, parameter t_{SFD} .

The nSS signal transition to low needs to be followed be a positive SCKL edge to high. Refer to Figure 28, parameter t_{DR1}.
The nSS signal transition to high terminates the command and starts the processing of the instruction.

The SPI slave provides a number of commands, that are selected by the 2-bit command ID (CID), listed in Table 10.

The SPI slave responses to the command with its next subsequent SPI frame as shown in Figure 29. The responses of the SPI slave are listed in Table 10.

The data of the memory can be accessed in two different ways:

- as a single command access
- as a multi command access processing a command queue.

Because the SPI transmits data bidirectionally at the same time, a request will be answered in the following SPI frame. The correct sequences of the command protocols are shown in Figure 29:

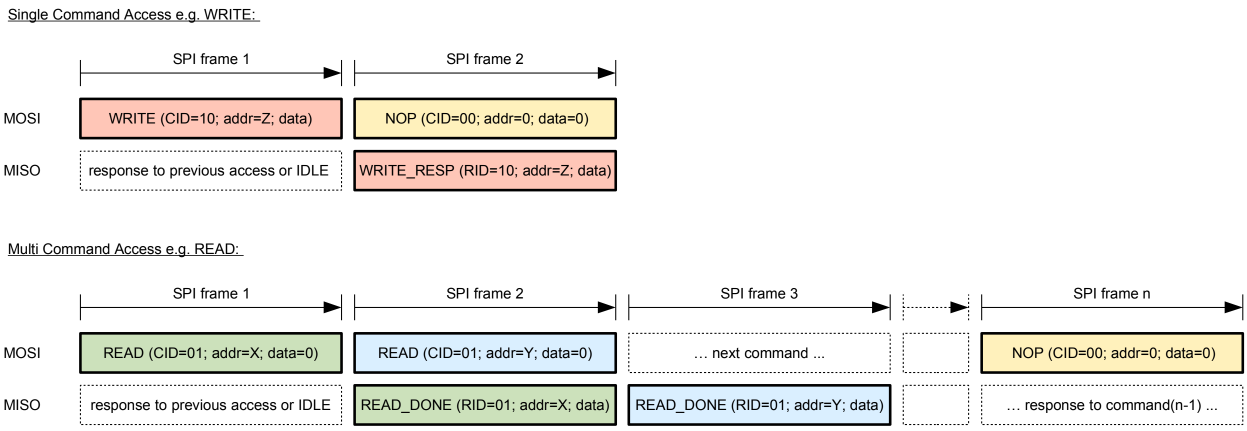

Figure 29: SPI command sequences

3.3. Communication error handling

Error detection

The error occurred if on MISO RID[0:1] = 11 and data[2:15] = 11'1111'1111'1111 is detected (refer to Figure 27 and Table 10).

Recovery sequence

No reset of the system is needed to recover from communication error condition on SPI. The recovery distinguishes into two sequences depending on the situation:

- Normal access
  If an error condition occurs because an SPI access to read/write register was performed (normal access), READ/WRITE was ignored and the user should just repeat READ/WRITE operation again.
- Data readout access (READ data)
  When an error condition occurs during performing a measurement and the readout of the data is in progress (data readout access), all the data from the current measurement is not valid (should be ignored) and the following sequence according Table 11 should be executed.

Word	SPI command sequence					SPI response sequence			
	Command	CID	Address	Data		Response	RID	Address	Data
No.		[1:0]	[7:2]	[15:8]			[1:0]	[7:2]	[15:8]
1	WRITE	0x2	0x33	0x59		…..	...	...	...
2	WRITE	0x2	0x34	0x00		WRITE_RESPONSE	0x2	0x33	0x59
3	WRITE	0x2	0x32	0x01		WRITE_RESPONSE	0x2	0x34	0x00
4	NOP	0x0	0x00	0x00		WRITE_RESPONSE	0x2	0x32	0x01
Wait predefined time > 4x integration time + 700µs									
5	WRITE	0x2	0x33	0x59		IDLE	0x0	0x00	0x00
6	WRITE	0x2	0x34	0x08		WRITE_RESPONSE	0x2	0x33	0x59
7	WRITE	0x2	0x32	0x01		WRITE_RESPONSE	0x2	0x34	0x08
8	NOP	0x0	0x00	0x00		WRITE_RESPONSE	0x2	0x32	0x01
Ignore data from current measurement. Go to start of next measurement.									

Table 11: Recovery sequence for data readout error

3.4. Start-up / load Parameter and configuration memory

The memory of the epc610 chip has a volatile and a non-volatile memory part (EEPROM).

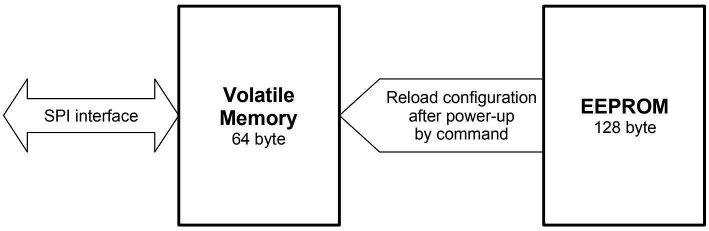

Figure 30: SPI and memory organization

The epc610 chip is using the configuration and the data from the volatile memory (see table Figure 30). It is organized by 64 bytes with 8 bits. It can be accessed by the SPI commands to write and read configurations, to start the measurement sequence and to read the data (refer to Table 13). The volatile data can be accessed at run-time by the SPI commands. These changes are lost if the device is powered down.

The EEPROM has 128 bytes with 8 bits and is not writable by the user. It contains the necessary factory settings for the chip. A copy of the data from the EEPROM can be reloaded as a whole at any time after the power-up sequence is finished.

After the power-up (max. 100ms), the factory configuration must be copied from the EEPROM to the volatile registers.

The command sequence to copy or restore the configuration data has to follow Table 12. The copy process starts with a WRITE command to the INDIRECT_COMMAND register. If the NOP polling answers with an IDLE response, the device has terminated the transfer. After this sequence, the full EEPROM data is present in the RAM and the chip is ready for operation.

Word	SPI command sequence					SPI response sequence			
	Command	CID	Address	Data		Response	RID	Address	Data
No.		[1:0]	[7:2]	[15:8]			[1:0]	[7:2]	[15:8]
3	WRITE	0x2	0x32	0x04		…..	...	...	...
4	NOP	0x0	0x00	0x00		WRITE_RESPONSE	0x2	0x32	0x04
5	NOP	0x0	0x00	0x00		BUSY	0x3	0x0C	0xCC
...	… NOP ...					… BUSY ...			
Send NOP until the response is IDLE									
8	NOP	0x0	0x00	0x00		IDLE	0x0	0x00	0x00
Configuration copy finished. The chip is ready for measurement.									

Table 12: Reload the factory setting from the EEPROM

3.5. Registers and user configuration parameters

This chapter describes all the parameter settings and the readable data by commands, which can be accessed or modified by the user.

Address	Bit								CMD	Register
	7	6	5	4	3	2	1	0		
0x00	1	INT [3]	0	0	0	INT [2:0]			WRITE	INTEGRATION
0x01										reserved
0x02	0	0	MEASURE [1:0]		1	0	0	0	WRITE	MEASUREMENT
0x03 - 0x19										reserved
0x1A	MOD_CLK_DIV [4:0]					0	0	1	WRITE	MOD_CLK
0x1B - 0x2D										reserved
0x2E	0	0	0	RDY	0	0	0	0	READ	STATUS
0x2F	SAT_P_7	SAT_P_6	SAT_P_5	SAT_P_4	SAT_P_3	SAT_P_2	SAT_P_1	SAT_P_0	READ	SAT_PIXELS
0x30 - 0x31										
0x32	refer to Table 11 and Table 12								WRITE	
0x33	refer to Table 11								WRITE	
0x34	refer to Table 11								WRITE	
0x35 - 0x3D										reserved
0x3E	DATA [7:0]								READ	DATA
0x3F	0	0	0	TRIG	1	0	0	1	WRITE	TRIGGER

Table 13: Address map of the volatile memory

The volatile memory map Table 13 gives an overview about the location of the parameters:

- The accessible parameters are located in the cells marked in white,
- whereas the gray-shaded areas are not available for user access.
- Partially gray-shaded registers can contain factory settings which shouldn't be changed.
  To prevent unexpected configuration changes, the user should read-back the complete register, modify only the respective (non-shaded) register bits and then write back the complete the register (This method is subsequently referred to as “Read-back, modify & write”.).

Note: Misuse of registers or commands lead to malfunction or can damage the chip.

3.5.1. Command: WRITE Integration time

Name:				INTEGRATION			Address:	0x00
Bit	7	6	5	4	3	2	1	0
Description	1	INT [3]	0	0	0	INT [2:0]		
Operation	reserved	read / write	reserved			read / write		

INT: Sets the integration time t_{INT} for the measurement during runtime.
Operation: Write complete register without read-back. Set reserved bits as defined above.

The integration times below in the table are for a LED modulation frequency of 10MHz. Refer also to chapter 1.3.2.: Unambiguity range and integration time base.

Time	INT	Time	INT	Time	INT	Time	INT
1.60 µs	11000111	25.6 µs	11000011	408 µs	10000111	6.56 ms	10000011
3.20 µs	11000110	51.2 µs	11000010	818 µs	10000110	13.2 ms	10000010
6.40 µs	11000101	103 µs	11000001	1.64 ms	10000101	26.3 ms	10000001
12.8 µs	11000100	205 µs	11000000	3.28 ms	10000100	52.6 ms	10000000

Note 1: For proper initialization, always write a valid integration time to the device after power-up.
Note 2: The command must be sent before the trigger command.
Note 3: A doubling of the integration time is equal to a doubling of the illumination in the scenery.

3.5.2. Command: WRITE Measurement type

Name:				MEASUREMENT			Address:	0x02
Bit	7	6	5	4	3	2	1	0
Description	0	0	MEASURE [1:0]		1	0	0	0
Operation	reserved		read / write		reserved			

MEASURE: Sets the measurement type.
Operation: Read-back, modify & write.

Description	MEASURE	DEFAULT
Measurement of the distance and the quality	00	X
Measurement of the ambient-light (ambient-light illuminated black & white image)	11	
Don't use	Others	

Note1: A measurement sequence (measurement time t_{MEAS}) always has 4 integration cycles independent of the type:
Distance and quality: Samples DCS0 – DCS3.
Ambient-light: 4 black & white images based on the ambient-light (DCS0 - DCS4).
Note 2: Needs to be set, if the measurement type has to be changed.
Note 3: The command must be sent before the trigger command.

3.5.3. Command: WRITE LED modulation clock

Name:			MOD_CLK			Address:		0x1A
Bit	7	6	5	4	3	2	1	0
Description	0	MOD_CLK_DIV [3:0]				0	0	1
Operation	reserved	read / write				reserved		

MOD_CLK_DIV: Divisor for the LED modulation clock.
Operation: Read-back, modify & write.

Range: 0 – 15d. This corresponds to a LED modulation frequency of 20MHz – 1.25MHz.
The LED modulation frequency defines the unambiguity distance and the distance resolution.

LED modulation frequency: $$f_{LED}[Hz] = \frac{20MHz}{MOD\_CLK\_DIV + 1}$$

Unambiguity distance: $$D_{unambiguity}[m] = \frac{MOD\_CLK\_DIV + 1}{20MHz} \cdot \frac{300'000'000m}{2}$$

For more details refer to chapter 1.3.2.: Unambiguity range and integration time base.

3.5.4. Command: READ Status

Name:				STATUS			Address:	0x2E
Bit	7	6	5	4	3	2	1	0
Description	0	0	0	RDY	0	0	0	0
Operation	reserved			Read only	reserved			

RDY: Wait for row ready. Indicates if a row is ready for readout with the command “READ Data”. Refer to Table 14.

Note: RDY bit is not defined after power-up and before first trigger command is sent.

<table>
<tr><th rowspan="2">Word No.</th><th colspan="4">SPI command sequence</th><th rowspan="2"></th><th colspan="4">SPI response sequence</th></tr>
<tr><th>Command</th><th>CID [1:0]</th><th>Address [7:2]</th><th>Data [15:8]</th><th>Response</th><th>RID [1:0]</th><th>Address [7:2]</th><th>Data [15:8]</th></tr>
<tr><td>1</td><td>READ</td><td>0x1</td><td>0x2E</td><td>0x00</td><td></td><td>Result of last command</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>READ</td><td>0x1</td><td>0x2E</td><td>0x00</td><td></td><td>READ_DONE</td><td>0x01</td><td>0x2E</td><td>xxx0 xxxx</td></tr>
<tr><td>...</td><td>… READ ...</td><td></td><td></td><td></td><td></td><td>… READ_DONE ...</td><td></td><td></td><td></td></tr>
<tr><td colspan="10">Send this READ command until.
1. Before starting the readout of a new DCS frame (Refer to Figure 13: After wait capture frame DCS0 – DCS3): READ_DONE switches to “1” for data bit 4 for two consecutive readings. If this is not the case, the first row of the next sample DCSx is not yet ready
2. During DCS frame readout sequence: READ_DONE switches to “1” for data bit 4</td></tr>
<tr><td>last</td><td>READ</td><td>0x1</td><td>0x2E</td><td>0x00</td><td></td><td>READ_DONE</td><td>0x01</td><td>0x2E</td><td>xxx1 xxxx</td></tr>
<tr><td colspan="10">Row ready. Start reading row data</td></tr>
</table>

Table 14: Sequence “Wait for row ready”

3.5.5. Command: READ Saturated pixels

Name:			SAT_PIXELS				Address:	0x2F
Bit	7	6	5	4	3	2	1	0
Description	SAT_P_7	SAT_P_6	SAT_P_5	SAT_P_4	SAT_P_3	SAT_P_2	SAT_P_1	SAT_P_0
Operation	read only	read only	read only	read only	read only	read only	read only	read only

SAT_P_x: Pixel saturation status for each pixel in the last converted row (current row).
The bit is set to "1" if the pixel is out of the linear operating range. The pixel sees too much modulated light or too much ambient-light.
Note: It is important to read the values of the register "SAT_PIXELS" before the readout of the data with the command "DATA". Refer to Figure 13. The readout of "SAT_PIXELS" is optional.

3.5.6. Command: READ Data

Name:			DATA				Address:	0x3E
Bit	7	6	5	4	3	2	1	0
Description	DATA [7:0]							
Operation	read only							

DATA: The streamed row data output (of the pixels and of the temperature) per sample DCS0 - DSC3 of the measurement sequence. Receives all rows of the DCSx frame with eight times doing the read cycles READ1 – READ15.

Responses to the command READ Data sequence:

Name:	DATA							
Bit	7	6	5	4	3	2	1	0
READ Data 1	PIXEL_0 [7:0]							
READ Data 2	PIXEL_1 [3:0]				PIXEL_0 [11:8]			
READ Data 3	PIXEL_1 [11:4]							
READ Data 4	PIXEL_2 [7:0]							
READ Data 5	PIXEL_3 [3:0]				PIXEL_2 [11:8]			
READ Data 6	PIXEL_3 [11:4]							
READ Data 7	PIXEL_4 [7:0]							
READ Data 8	PIXEL_5 [3:0]				PIXEL_4 [11:8]			
READ Data 9	PIXEL_5 [11:4]							
READ Data 10	PIXEL_6 [7:0]							
READ Data 11	PIXEL_7 [3:0]				PIXEL_6 [11:8]			
READ Data 12	PIXEL_7 [11:4]							
READ Data 13	TEMPERATUR_0 [7:0]							
READ Data 14	TEMPERATUR_1 [3:0]				TEMPERATUR_0 [11:8]			
READ Data 15	TEMPERATUR_1 [11:4]							

PIXEL_x: MSB and LSB part of the 12 bit pixel data (DCSx).

DCSx data for the distance and the quality:
Data format: signed 12 bit integer (two's complement), units: LSB, A/D conversion values
For the distance calculation, refer to chapter 1.3.1: Distance measurement.
For the quality calculation, refer to chapter 1.3.5: Quality of the measurement result.

Typical distance values for 10MHz LED modulation frequency are after the calculation and without the corrections e.g.:
1 LSB = 0.5 cm. Minimum DIST = 0d ≙ 0m. Maximum DIST = 3'000d ≙ 15m

Pixel data for the ambient-light values (optical power-meter):
Data format: signed 12 bit integer (two's complement), units: LSB, A/D conversion values
Note: Small negative number can occur due to noise.
For the ambient-light calculation, refer to chapter 1.3.6: Ambient-light measurement (optical power-meter)

TEMPERATUR_x: MSB and LSB part of the 12 bit temperature 0 and 1, measured at the opposite sides of the pixel area at the sampling time. Data format: unsigned 12 bit integer, units: LSB, A/D conversion values,

Notes:

- A complete measurement sequence includes the 4 samples DCS0 – DCS3 (integrations), each with a dataset of 8 rows containing 15 bytes of pixel and temperature data (refer to Figure 13).
- Before reading, wait until the next “Capture frame” (integration) is ready and/or the “Load next row” is finished. You can wait either by using the timer or by status reading:
  - by timer (for t_{INT} refer to chapter :):
    Waiting time for one integration cycle: 1st sample: t_{INT} + 82µs (Wait capture frame)
    next samples: t_{INT} + 50µs (Wait capture frame).
    Waiting time for the next row: 16µs (Wait load next row).
  - by status reading “Wait for row ready”. Refer to command “STATUS”:
    The command reads the status of the epc610 chip and checks if the next row is loaded. In that case, no additional waiting times for the samples or rows are necessary.
    Note: The first time after each integration (catching the next sample DCS0 – DCS3), the user needs to read a “Row ready” twice consecutively. If this is not done, the first row of the next sample DCSx will not yet be ready.
- Do a read-out of the 4 total samples with 8 times the Read 1 – Read 15 command consecutively and without any discontinuity. This is the reading of the 4 complete frames of one measurement cycle.
- Close the reading sequence with a NOP command to get the last data (output of Read 15).

ERROR handling:

- Once the sequence is started, it cannot be terminated until the end. All data needs to be read before the chip accepts the next trigger operation.
- Reading data before the next row is loaded, either asynchronously or over the end of the sequence, will give erroneous data without notice (Read-out of old data).
- **If the synchronism of the reading is lost, the remaining measurement data is not any longer valid. A resynchronization of the protocol can be done according the recovery sequence for the data readout access (READ data), refer to chapter 3.3. Communication error handling. The next trigger then returns the chip to a synchronized data output.**
- Type or time commands during the sequence are not ignored and change the corresponding mode on the fly. It can lead to non merged datasets.

3.5.7. Command: WRITE Set trigger

Name:	TRIGGER						Address:	0x3F
Bit	7	6	5	4	3	2	1	0
Description	0	0	0	TRIG	1	0	0	1
Operation	reserved			read / write	reserved			

TRIG: Sets the trigger active for a sampling sequence of 4 samples (integrations) ≙ 1 complete measurement sequence. Operation: Write complete register without read-back. Set reserved bits as defined above.

Description	TRIG	DEFAULT
Triggers the next sequence	1	
Trigger not active. The signal is cleared by the chip after the start of the measurement sequence.	(0)	X

Note 1: Set the correct measurement type before the trigger command.
Note 2: To start the measurement sequence, send a NOP after the trigger command.
Note 3: Read all 4 samples after a trigger command, independent of the measurement type (refer to chapter 3.5.6.: Command: READ Data).
Note 4: Trigger bit is not defined after power-up and before first trigger command is sent.

3.5.8. Examples of SPI command sequences

The MOSI and MISO data sequences for the most important SPI commands are listed here in Table 15 as examples.

Action	Command	MOSI	MISO	Comment
"Power up":	NOP: After start up	0x 00 00	0x	
	- repeat until:			
	NOP: Ready for communication	0x 00 00	**0x 00 00**	IDLE
"Factory setting":	Download EEPROM	0x B2 04	0x 00 00	
	NOP: Loading RAM	0x 00 00	0x B2 04	
	NOP: Loading RAM	0x 00 00	0x CC CC	BUSY
	- repeat until:			Waiting time approx. 105µs
	NOP: Download finished	0x 00 00	**0x 00 00**	IDLE
"Set LED mod. freq.":	Set LED mod. freq. 10MHz	0x 9A 09	0x 00 00	Optional, 10MHz is the factory default value
	NOP	0x 00 00	0x 9A 09	NOP is optional
"Set integration time":	Set int. time 103us	0x 80 C1	0x 00 00	
	NOP	0x 00 00	0x 80 C1	NOP is optional
"Start Measurement":	Set TRIGGER	0x BF 19	0x 00 00	
	NOP: Start measurement	0x 00 00	0x BF 19	NOP is mandatory to start measurement
"Read frame DCSx":				Repeat this procedure 4 times per measurement
	Read STATUS	0x 6E 00	0x 00 00	
	Read STATUS	0x 6E 00	0x 6E ..	
	- repeat until:			Waiting time: see command READ data, notes
	Read STATUS	0x 6E 00	**0x 6E 10**	1st time RDY: Integration finished
"Read row":				Repeat this procedure 8 times per frame
	- repeat until:			Waiting time: see command READ data, notes
	Read STATUS	0x 6E 00	**0x 6E 10**	2nd time RDY or next RDY after row
	Read SAT_PIXELS	0x 6F 00	0x 6E 10	
	READ data 1	0x 7E 00	0x 6F ..	Result SAT_PIXELS
	READ data 2	0x 7E 00	0x 7E ..	Result data 1
	READ data 3	0x 7E 00	0x 7E ..	Result data 2
	READ data 4	0x 7E 00	0x 7E ..	Result data 3
	READ data 5	0x 7E 00	0x 7E ..	Result data 4
	READ data 6	0x 7E 00	0x 7E ..	Result data 5
	READ data 7	0x 7E 00	0x 7E ..	Result data 6
	READ data 8	0x 7E 00	0x 7E ..	Result data 7
	READ data 9	0x 7E 00	0x 7E ..	Result data 8
	READ data 10	0x 7E 00	0x 7E ..	Result data 9
	READ data 11	0x 7E 00	0x 7E ..	Result data 10
	READ data 12	0x 7E 00	0x 7E ..	Result data 11
	READ data 13	0x 7E 00	0x 7E ..	Result data 12
	READ data 14	0x 7E 00	0x 7E ..	Result data 13
	READ data 15	0x 7E 00	0x 7E ..	Result data 14
	Read last data	0x 00 00	0x 7E ..	Result data 15, NOP is optional
"Next row":	**- repeat "Read row" for next 7 rows**			
"Next DCSx":	**- repeat "Read frame DCSx" for next 3 DCSx frames**			
"End measurement"				

Table 15: Most important SPI command sequences

3.5.9. Cycle time calculation

The following example shows the estimation of the measurement cycle time t_{CYCLE}.

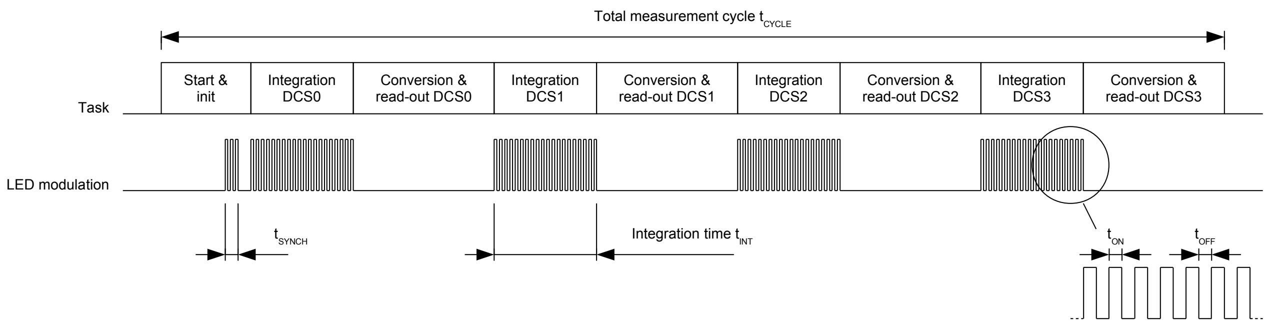

Figure 31: Measurement cycle timing

The above timing diagram contains in detail the following tasks:

No.	Task	Done by	SPI data frame [bit]	Time used [μs]
1.	Start measurement	µC	2 SPI commands x (16 SPI bits + 1 nSS pulse) = 34 bits	3
2.	Init	epc610	8 rows x 18 SPI commands x (16 SPI bits + 1 nSS pulse) = 2'448 bits	70
3.	Integration to acquire DCS0	epc610		51
4.	Conversion	epc610		175
5.	Readout DCS0	µC	8 rows x 18 SPI commands x (16 SPI bits + 1 nSS pulse) = 2'448 bits	245
6.	Integration to acquire DCS1	epc610		51
7.	Conversion	epc610		175
8.	Readout DCS1	µC	8 rows x 18 SPI commands x (16 SPI bits + 1 nSS pulse) = 2'448 bits	245
9.	Integration to acquire DCS2	epc610		51
10.	Conversion	epc610		175
11.	Readout DCS2	µC	8 rows x 18 SPI commands x (16 SPI bits + 1 nSS pulse) = 2'448 bits	245
12.	Integration to acquire DCS3	epc610		51
13.	Conversion	epc610		175
14.	Readout DCS3	µC	8 rows x 18 SPI commands x (16 SPI bits + 1 nSS pulse) = 2'448 bits	245
Total measurement cycle				1'937

Table 16: Timing example of a measurement cycle

This example uses an integration time of 51µs and an SPI clock frequency of 10MHz.

*) Please note that an object or camera movement between task No. 3 and 12 may lead to false measurement data.

LED on-time and LED duty cycle

For the power dissipation estimation of the emitter LED (at pin LED), the LED on-time t_{LED_ON} and the duty cycle $DC_{LED\text{-}ON}$ are of importance. The following time periods have to be taken in consideration:

- During the integration period t_{INT}: the LED outputs are active for 50% of the time.
- There are 4 integration periods t_{INT} per measurement cycle t_{MEAS}.
- During the SPI communication, the LED outputs are not active.

The formula for the LED on-time is: $t_{LED-ON} = 4 \cdot \frac{t_{INT}}{2} + \frac{t_{SYNCH}}{2}$ e.g. $t_{LED\text{-}ON} = 4 * \frac{51\,\mu s}{2} + \frac{30\,\mu s}{2} = 117\,\mu s$

The LED duty cycle $DC_{LED\text{-}ON}$ for the LED on-time versus the cycle time is

$$DC_{LED-ON} = \frac{t_{LED-ON}}{t_{CYCLE}} \quad \text{e.g.} \quad DC_{LED\text{-}ON} = \frac{117\,\mu s}{1'937\,\mu s} = 6\%$$

4. Optical Design Considerations

This section summarizes some parameters that are of importance when designing the optical system of a TOF imager.

Photosensitive area

The photosensitive area of the sensor is the optical free area which has to be well (full) covered by the illumination optics.

The photosensitive area of the pixel is the relevant surface for calculating the light sensitivity of the chip (pixel).

Note:
Measurement values are reliable only if the object covers the entire photosensitive area of the pixel. Refer to the epc600 Handbook.

Signal sensitivity

The signal sensitivity is defined by the minimum and maximum detectable AC modulation signal (reflected light). It is defined by the light power (Watt/m^2) in relation to:

- the photo-sensitive area of the pixel.
- the operating integration time t_{INT} .
- the operating wavelength λ.
- the angle of incidence (or reflectance of the sensor surface). Refer to Figure 3.

It is independent of
- the modulation frequency

Ambient-light suppression

The ability to suppress DC or low-frequency modulation parts of the received light signal. It is defined by the light power (Watt/m^2) in relation to:

- the photo-sensitive area of the sensor.
- the operating integration time t_{INT}.
- the operating wavelength λ.
- the angle of interest (or reflectance of the sensor surface). Refer to Figure 3.

Refer also to chapter 1.3.4: Ambient-light suppression.

Operating range

The maximum non-ambiguity distance is < 15m for a modulation frequency of 10MHz @ the pin LED. It is given by the modulation frequency and the time-of-flight.

The operating range (dynamic range) of the epc610 receiver for a certain illumination level is given by the photosensor and its electronics:
- the AC signal sensitivity for the modulated light.
- the capability of the ambient-light suppression.
- the level of illumination.

Depending of the optical design, these ranges do not match. The optical engineer has to plan the optical design and the light power in a way that matches the application best.

For more detailed information refer to epc's application note AN02 - Reflected power calculation.

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