intensified sCMOS

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Content

1 Motivation for image intensification

Image intensifiers increase the intensity of the available light in a system, allowing better image reproduction in low light scenarios. But with advancements in camera technologies, do we still need image intensifier cameras? To answer this question, it may help to investigate the challenges which necessitate the application of this elaborate technology.

For practical scientific applications, image intensification was historically the best way to extract valuable information out of just a few emitted photons. Presently, this is no longer the case. When there are few photons to capture, emCCD and more recently sCMOS have become the methods of choice because of advantages ranging from image quality and resolution to easy handling.

But intensification is still useful if the few photons have to be detected in an **extraordinary short exposure time of a few nanoseconds**, which emCCD and sCMOS cannot match. Image intensifiers allow such extremely short exposure times - often referred to as **gating**. Nanosecond exposure times are about 6 orders of magnitude shorter than the corresponding sensor readout times even when the intensifier is coupled with fast state of the art sCMOS sensors. Thus it is essential that the “light leakage” into the readout process is extremely small. This leakage rate is best described quantitatively by the term **shutter ratio**. Proper synchronization and control of the different components that shape the light signal path can achieve shutter ratios better than 10^{-9}.

Typical CCD or CMOS reaction times to an external trigger event are at least a few microseconds. This is understandable, as clearing the pixels prior to starting the accumulation of photo electrons requires that time to be effective. Switching the photocathode of an image intensifier from closed to open can be effected with a much shorter latency — **response times of less than 50 nanoseconds** are feasible. Thus, optical events with a very short pre-alert time, out of reach for CCD and CMOS sensors, can be captured with image intensification technology.

Also of scientific importance is the application of image intensifier technology for the detection of VUV (Vacuum Ultra-Violet) radiation down to 120 nm.

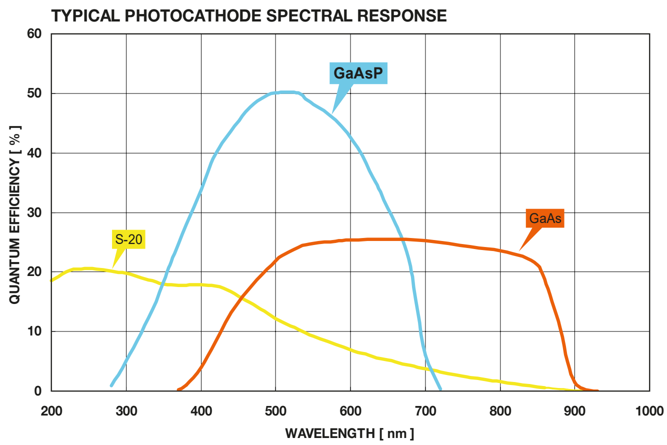
2 Principle of image intensification

As direct intensification of the input light is not feasible, the loop way of converting light into electrons-amplification of the electron signal and re-conversion of the electrons back into a photonic signal must be chosen.To achieve this intensification, an image intensifier tube consists of three main functional components: photocathode, micro channel plate, and phosphor screen, as depicted in Figure 2. We will have a closer look at each component in the following three sub-chapters.

2.1 Photocathode

The photocathode is a thin layer of a few micrometers that is deposited directly onto the backside of the input window of the image intensifier tube. Depending on the chosen material and the wavelength of the incoming photons, the photocathode absorbs them and, in exchange, emits electrons into the vacuum between input window and micro channel plate. The underlying mechanism of generating free electrons (or photoelectrons) is based on the external photoelectric effect. Figure 1 shows the spectral quantum efficiency of 3 different photocathode materials, all having a low work function, allowing for easy emission of excited electrons into the vacuum band where they are free and no longer bound to the photocathode. S20 material is widely used and has a high response in deep UV and a large sensitivity range up to 800 nm. Conversely, GaAsP material is perfectly suited for the visible range of 450 to 700 nm, and GaAs covers VIS and the NIR.

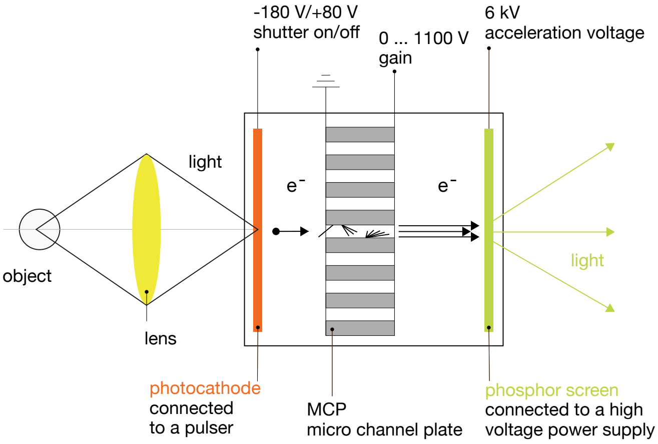
Figure 1: quantum efficiency of different photocathode materials as a function of wavelength



A careful selection of the proper photocathode material for the planned application is up to the user. Photocathodes are not interchangeable on their own – the whole image intensifier must be switched, which is costly.

The photocathode is key for the shutter ratio, defined as the ratio of the brightness on the phosphor screen during gate ON to that during gate OFF at continuous and constant illumination. The shutter ratio of an image intensifier can reach high numerical values but is strongly dependent on the wavelength of the incoming light and the photocathode material. Beside the conversion of photons into electrons, the photocathode is also the functional part, where the gating occurs. Gating is understood as the ultra-fast switching between +80 V (OFF) and -180 V (ON) potential between photocathode and MCP (micro channel plate) input (Figure 2). A very special electronic circuitry is necessary to achieve pulses with rising times of 260 V/ns.

Figure 2: functional principle of a gated image intensifier



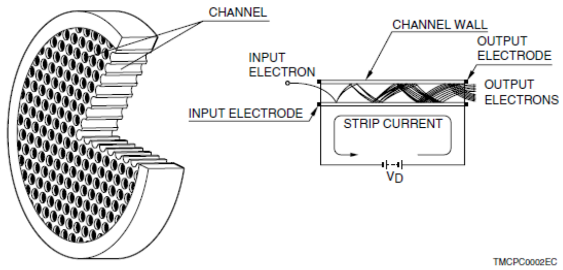
2.2 Micro Channel Plate (MCP)

The MCP is an electron multiplier that detects and multiplies electrons in two dimensions. When the accelerated photoelectrons emitted from the photocathode enter the tilted MCP channels, they are further accelerated by the MCP bias and hit the channel wall (Figure 3). Due to their excess energy, they produce secondary electrons which travel on parabolic trajectories and strike the opposite wall, thus producing more secondary electrons. This process is repeated many times along the channel. As a result, a large number of electrons is released from the output side.

Figure 4 shows the structure of a high resolution MCP under the microscope. A thin array of tiny 6 µm glass channels becomes visible. 25 mm diameter high resolution MCPs used in PCO cameras are about 0.5 mm thick (equal to the length of channels) and have about 10,000,000 channels. Each channel works as an independent electron multiplier driven by voltages of up to 1100 V. Theory sets the MTF limit to 83 lp/mm. Taking geometric effects into account, maximum MTF values for high quality image intensifiers reach up to 64 lp/mm at 5 % visual contrast. The ratio between the channel diameter and the total length of the channel defines the maximum possible gain.

High gain of electronic signals depletes the micro channel walls of electrons. Therefore, an important characteristic of an MCP is a low resistance of 20 – 30 MΩ which allows high strip currents necessary for short reload time during repetitive operation. If the MCP resistance is too high, or the frequency with which signals are intensified is too fast, the resulting depletion of the affected MCP channels will show up as spatially reduced gain. Negative-like images with inverted intensity distribution are a clear sign that the MCP reload could not be effected fast enough.

Figure 3: MCP structure and operation



drawing courtesy of Hamamatsu Photonics

Figure 4: MCP, microscopic image

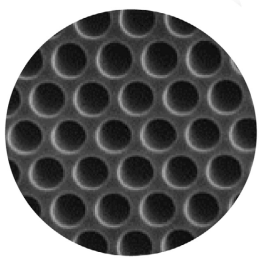
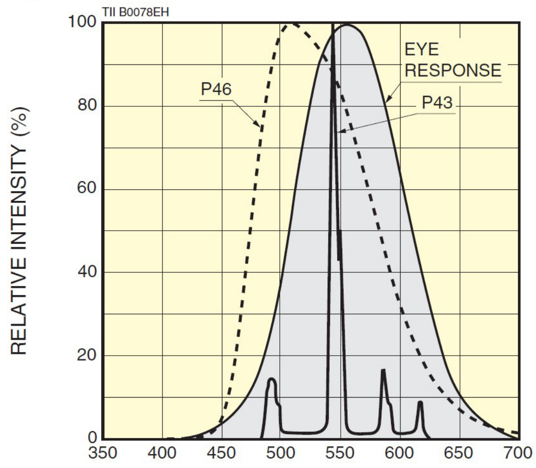
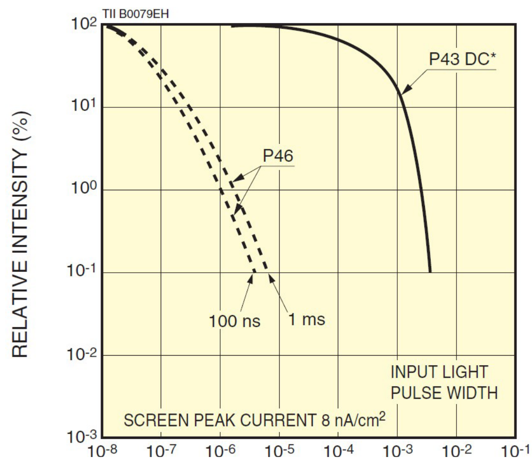


Figure 5: spectral emission characteristics of different phosphor materials



drawing courtesy of Hamamatsu Photonics

Figure 6: decay time of different phosphor materials



drawing courtesy of Hamamatsu Photonics

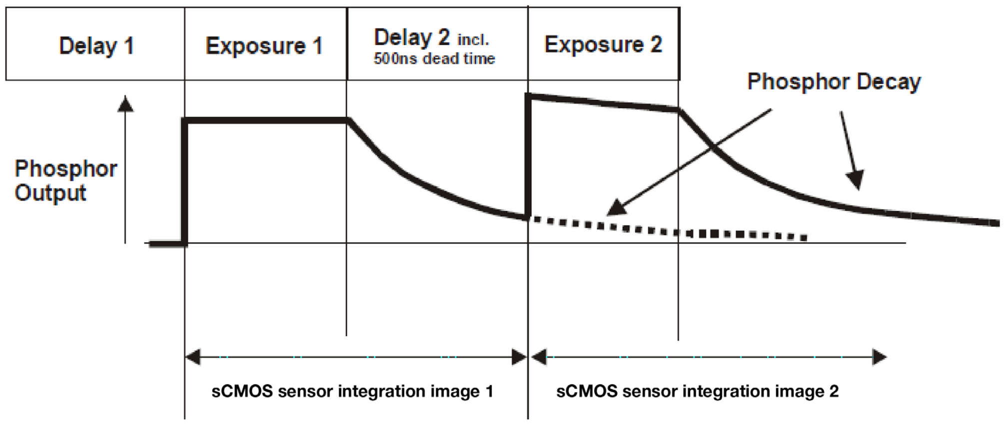
2.3 Phosphor screen

Phosphor screen is the third component of the image intensifier and responsible for the optical output. Its function is to absorb highly accelerated electrons (6 – 7 kV static voltage) coming from the MCP output and convert them back into photons. Like the photocathode, the phosphor is a thin layer on the inner side of the output window. Contrary to the name, these layers do not contain the element phosphor.

P46 phosphor, for example, is made of yttrium aluminium garnet – better known as YAG, a well-known laser material. Figure 5 gives the spectral emission characteristics of 5 different phosphor materials and shaded in grey is spectrum curve visible to the human eye. Key requirements for phosphor selection are sufficient brightness and an emission range which matches the camera module's QE curve. Note that there are also differences in optical quality. P43, for example, has a homogeneous crystallite size, whereas P46 is more heterogeneous. The emission of P43 is smoother and much brighter than that of P46.

A second important criterion for phosphor selection is its decay time. This means the characteristic time frame in which phosphor light emission decreases after electron impact has stopped (Figure 6). Fast phosphor decay is especially useful when it's needed to capture two images in succession within a few hundred nanoseconds — often referred to as "double image mode" or PIV mode. This is illustrated in figure 7. A slowly decaying phosphor might mix image information of Exposure 1 into Exposure 2 and therefore spoil the contents of image 2.

Figure 7: double image acquisition with short interframing time and a phosphor with too long decay time

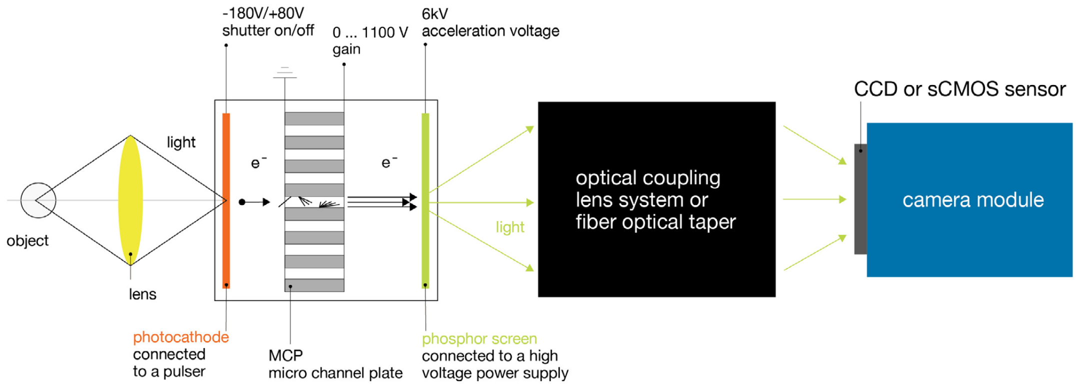


2.4 Functional schematic of an intensified camera

A fully functional integrated intensified camera system requires optically coupling the image intensifier — consisting of photocathode, MCP and phosphor screen — to the CCD or sCMOS detector of a camera module (Figure 8).

Additionally, the electronic control of the intensifier unit must be precisely synchronized with the image acquisition of the camera module so that the latter captures the image content on the phosphor at exactly the right time.

Figure 8: components and functional principle of an intensified camera system



3 Comparison of optical coupling methods

It's been a long and controversial discussion about the best way to achieve the optical coupling between the phosphor output of an image intensifier and the CCD/sCMOS sensor of a camera module. Basically, there are two distinct methods to accomplish this – fiber optical taper or imaging lens(es). A common argument made in support of fiber optical taper is:

"A properly fabricated fiber optical taper offers transmission efficiencies up to 60 %, whereas a lens coupling stays in the single digit percentage range. Therefore, the taper coupling method is superior to the lens coupling as it delivers much more of the phosphor light to the pixels."

To understand and form a well-rounded opinion, a thorough comparison must be made, including all aspects from theory to practical implementation.

3.1 Taper coupling

A taper coupling uses a bundle of fibers to transfer the light, point-by-point, from the phosphor output of an image intensifier to the sensor (Figure 9). Light is guided and kept within a single fiber based on the principle of total internal reflection between the core and the cladding. To achieve this, the transmitting core with high refraction index is covered by a lower refractive index cladding. The angle of the incident light as defined by Snell's law must be within the acceptance cone for a successful transmission (Figure 10).

Figure 9: path of light from the phosphor output (left side, green) of an image intensifier to the pixel matrix of a CCD or sCMOS image sensor (right side)

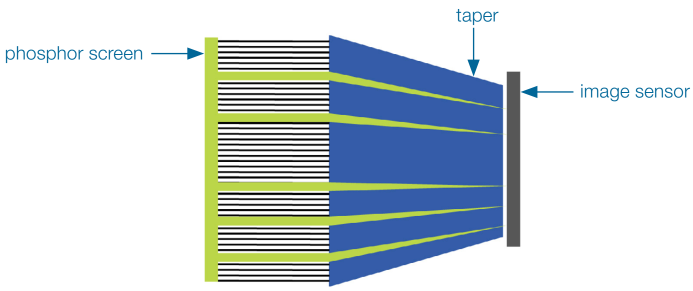
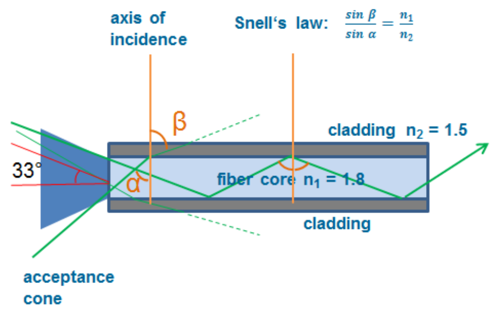


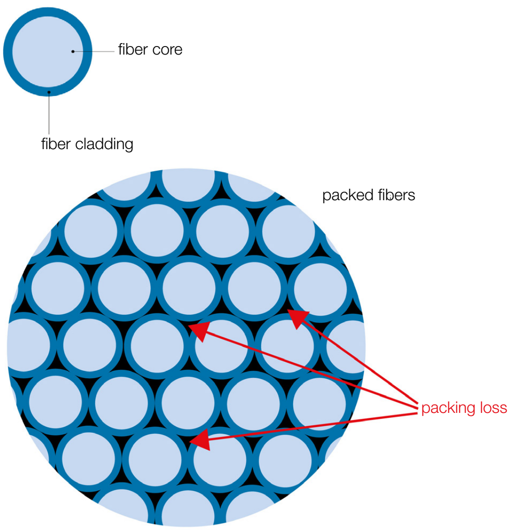
Figure 10: principle of light ray propagation through a single fiber. to simplify the drawing it is assumed that the refractive index ouside the fiber is n_1 = 1.8



Single fibers are packed and fused to bunches. These bunches are bundled and fused once more to finally form the taper. As it is not possible to focus with a taper, the phosphor output of the intensifier needs a directly attached fiber optical plate (FOP) as support. A glass support would cause an out of focus image.

Therefore, the taper must be coupled on both sides - to the FOP of the phosphor and to the pixel matrix of the sensor. There are always two fiber optical elements involved in a fiber optical coupling, a fact that is important to remember when we estimate the losses of a real taper coupling later. The maximum theoretical transmission efficiency of a perfect 1:1 taper (input diameter = output diameter) can be calculated under the additional assumptions that all input light is collimated or within the acceptance cone and that the fiber diameter is larger than 5 µm.

Figure 11: structure of a single fiber and many fibers packed within a taper



The transmission efficiency of such a perfect taper starts at 64 %. In this perfect case, only 8 % reflection loss, 17 % cladding loss, and 11 % packing loss are considered. The manufacturing process typically adds another 4 % loss for real tapers. Under these assumptions a single taper or FOP will transmit 60 % of the light input to the other end where it is emitted (Reference 1).

And this is before it reaches the pixel! None of the additional losses attributed with the 2-staged transmission over FOP and taper and the coupling losses at the pixel layer have been considered yet. (See next page **Signal loss mechanisms for taper couplings)**. The scenario above with a large fiber diameter and 1:1 imaging ratio is an ideal condition but reality is often different. Let's consider the influence of demagnification and fiber diameter on transmission efficiency.

To resolve high resolution phosphors the use of smaller fiber diameters of 2 - 3 µm could make sense. But in this case, the area ratio between fiber core and cladding is negatively affected and the transmission efficiency drops down from 60 % to 40 %.

Also, the strong influence of de-magnification on the transmission efficiency of tapers is often overseen. As can be seen from formula 1, reducing the image size e.g. with a 2:1 taper decreases the 60 % of a perfect 1:1 taper with > 5 µm fibers down to 15 %. Unfortunately, demagnification does not increase the light concentration as one might expect, in fact the opposite is true.

FORMULA 1

De-magnification: $$T_{result} = T_{max} \times \frac{D^2_{min}}{D^2}$$

T_{max}: theoretical transmission efficiency for a perfect 1 : 1 taper with fiber diameter > 5 µm

D_{min}: taper diameter at the small end
D: taper diameter at the large end

Example: phosphor to sCMOS sensor image scaling with taper coupling

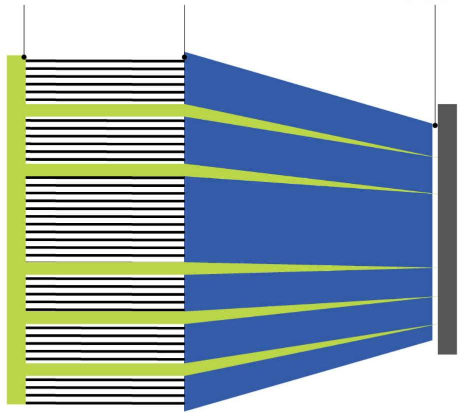
As a consequence of the above calculated efficient 1:1 image scaling, only the smaller 18 mm image intensifiers can be used for a 4.2 MPixel sCMOS sensor with 18.8 mm diagonal. For the preferred high resolution 25 mm intensifiers, de-magnifying tapers with drastic efficiency loss must be used:

FORMULA 2

$$T_{result} = T_{max} \times \frac{18.8^2}{25^2} = 0.57 \times T_{max}$$

Signal loss mechanisms for taper couplings
As shown previously, the transmission efficiency of a single taper is impressively high when looked at as an isolated device. But using it to couple the optical output of an image intensifier phosphor screen into the pixel matrix of a CCD or sCMOS detector, the story becomes more delicate. The light emission must be coupled into the fiber bundle first and - what is even more critical - it must be fed into the pixel matrix on the camera end of the connection. In- and out-coupling of the light to and from a taper is where significant losses occur, making the overall transmission efficiency of a taper comparable with that of a well-adjusted tandem lens system.

Figure 12: relevant interfaces within the path of light from the phosphor output (left side, green) of an image intensifier to the pixel matrix of a CCD or sCMOS image sensor (right side)



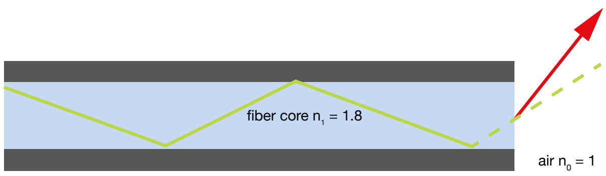
Three interfaces must be considered:

A: Interface between phosphor and FOP input
B: Interface between FOP output and taper input
C1: Interface between taper output and pixel surface for air coupling
C2: Interface between taper output and pixel surface for glue or immersion oil coupling

Interface A: Taper couplings require an image intensifier with fiber optic plate (FOP) as output, in other words, the phosphor material is deposited on a FOP. The light leaving the phosphor with a spread of 180° can only enter the FOP and propagate in the desired way if its angle is below the total reflection limit as defined by the acceptance cone. In addition, there is cladding and packing loss as described above. Therefore, the basic light output of such an intensifier with FOP is about 30 % weaker (Reference 2) than that of an image intensifier with glass output under otherwise identical conditions.

Interface B: The same loss mechanisms apply a second time when the light leaves the FOP and enters the taper. Due to the change of refraction index, the light emitted from the FOP is partially outside of the acceptance cone. Again, cladding and packing loss must be considered. Therefore, the equivalent of two fiber optical devices needed for a proper taper coupling almost double the characteristic losses of a single taper.

Figure 13: the emission angle of light leaving a fiber is increased due to the change of refraction index



Interface C1: For an air coupling of the taper output onto the pixel, the change in refraction index increases the proportion of light emission under larger angles (Figure 13). The micro lenses on top of the pixels, as shown in figure 14, are very sensitive to that. Their focusing capabilities decrease significantly with larger angles. Consequently, the pixel's quantum efficiency goes down as can be seen from figure 15, shown exemplary for the CIS2521 image sensor.

Figure 14: pixel schematic with photo active area and micro lens

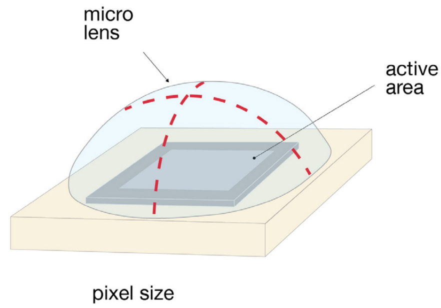
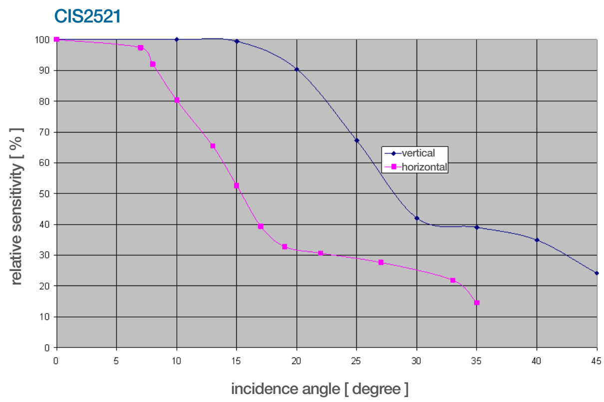
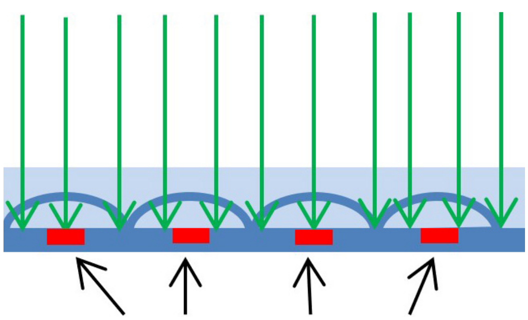


Figure 15: relative sensitivity as a function of the angle of incidence of the photons



Interface C2: To avoid the negative effect of the abrupt change of the refractive index from 1.8 in glass to 1 in air, the output side of a taper is often coupled to the pixel surface using immersion oil or optical glue. But doing so is like cutting away the micro lenses because their curvature, which is necessary to focus the photons to the photodiode, is filled up with material of similar refractive index (the oil or glue, Figure 16). Again, the effect is equivalent to a significant decrease in the pixel's quantum efficiency.

Figure 16: photons lost for detection due to ineffective micro lens array



3.2 Single lens coupling - and why PCO avoids it

Figure 17 shows the imaging geometry for a single lens coupling. With a single lens of focal length f, the phosphor with glass output in object distance g is imaged onto the detector in image distance b. These distances are measured in both directions from the lens position. The relationship between these two distances is at first order defined by the well-known imaging equation for lenses 1/b + 1/g = 1/f. The transmission efficiency for a single lens coupling is calculated according to formula 3. Even a high aperture 50 mm lens with F1.0 would result in only 5.9 % transmission efficiency for a 1:1 imaging ratio.

FORMULA 3

Imaging equation for a single lens with focal length f

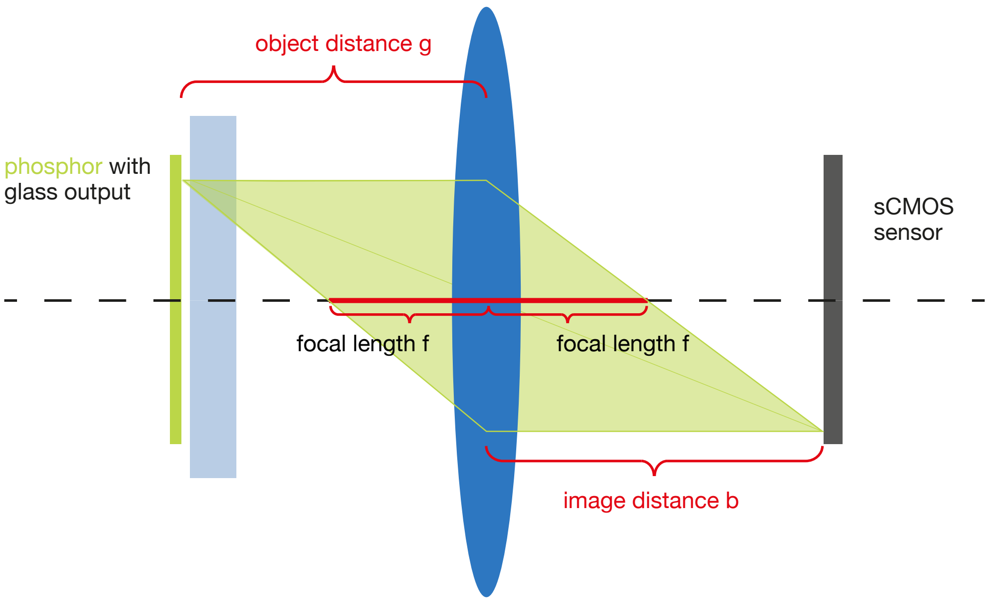
$$\frac{1}{b} + \frac{1}{g} = \frac{1}{f}$$

transmission efficiency for single lens:

$$\eta = \frac{1}{4k^2(1+\beta)^2+\beta^2}$$

with: $\beta = \frac{b}{g}$, $k = \frac{f}{d}$, d = lens diameter

Figure 17: imaging geometry for a single lens coupling



3.3 Tandem lens coupling – and why it is PCO's choice

A tandem lens system consists of two lenses (Figure 18). The imaging path goes from the focal plane of the first lens (L1 = collimator lens) to infinity so that all rays emitted from a single object point are converted into a parallel bunch of rays. The second lens (L2 = imaging lens) is focused to infinity and therefore brings this parallel bunch of rays back to focus in a single image point in the focal plane where the sensor is positioned. The phosphor of a lens coupled image intensifier has a glass output because the lens can focus on the phosphor plane through the glass.

The transmission efficiency of a tandem lens system can be calculated using formula 4. In this example, for an advanced tandem lens system consisting of a F1.5 collimator lens of 100 mm focal length and a F0.85 imaging lens of 53 mm focal length, the calculation gives a transmission efficiency of 31.2 %, which is in good accordance with measurements.

FORMULA 4

transmission efficiency for a tandem lens:

$$\eta = \frac{1}{4k^2\beta^2+\beta^2} \times \frac{d_2^2}{d_1^2}$$

with $\beta = \frac{f_2}{f_1}$ $k = \frac{f_1}{d_1}$,

d_1, d_2 : aperture of L_1 and L_2

As both lenses are used just for this single imaging task – within a narrow spectral range from focal plane to infinity and from infinity back to focal plane – their optical design can be perfectly optimized without any compromise. This optimization guarantees high transmission efficiency as well as perfect image quality free of artifacts. Another distinct advantage of the contact-less coupling system is that potential contamination will always stay outside the focal planes of both lenses and therefore do not affect the image quality.

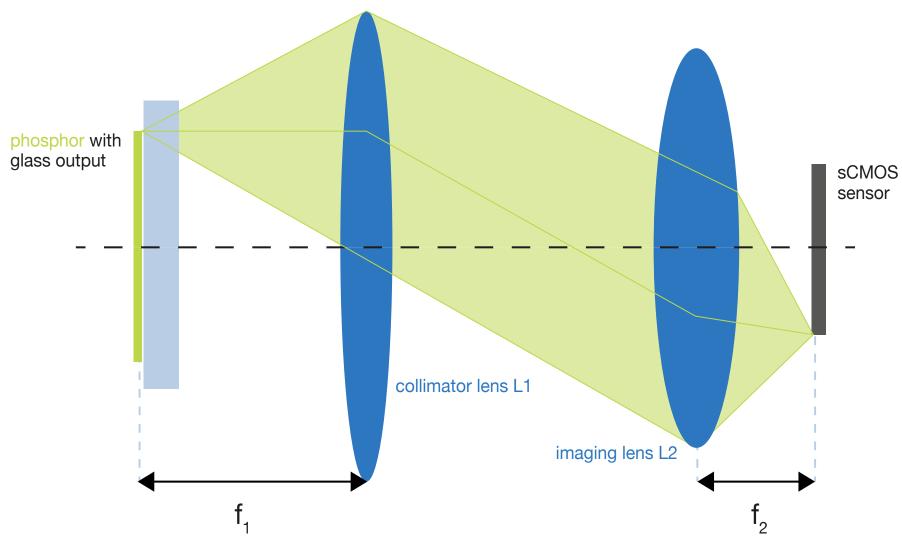
Adaptation of the imaging scale between phosphor diameter and its image on the detector is ruled by the ratio of the focal lengths of these two lenses and can easily be adjusted to the required needs (see formula 5).

FORMULA 5

$$\beta = \frac{f_2}{f_1} = \frac{53}{100} = 0.53$$

This result shows that the combination of the two lenses with 100 mm and 53 mm focal length, as used in the new pco.dicam C1, is suitable for imaging the optical output of a 25 mm phosphor to the sCMOS sensor with a diagonal of 18.8 mm.

Figure 18: imaging geometry for a tandem lens coupling



3.4 Conclusion

Revisiting the statement we cited at the beginning of chapter 3:

"A properly fabricated fiber optical taper offers transmission efficiencies up to 60 % whereas a lens coupling stays in the single digit percentage range. Therefore, the taper coupling method is clearly superior to the lens coupling as it delivers much more of the phosphor light to the pixels."

We now must limit its validity to the following restrictive and non-realistic conditions:

The statement is true, but only if ...

1. you do not take into account the significant losses at the point where the light is coupled into the taper and where it is coupled out from the taper into the detector's pixel.
2. you compare taper coupling with imaging ratio 1:1 to the coupling by a single lens and not to the state-of-the-art coupling by a much more efficient tandem lens system.

To summarize the results we have collected so far:

Theoretical transmission efficiencies for fiber optical tapers of up to 60 % cannot be achieved in practice due to various loss mechanisms affecting light propagation over the three interfaces A, B, C of a real taper coupling.

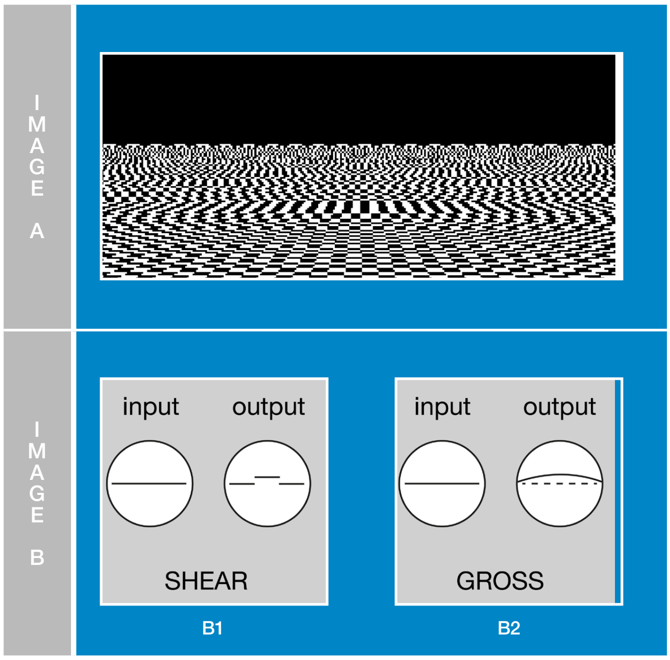
Image quality - image antifacts of fiber optical tapers

Up to this point, we have only considered the quantitative side of taper couplings. However, qualitative aspects should not be neglected, especially image quality. The high optical quality of a state-of-the-art tandem lens coupling has already been described above.

There is a long list of commonly observed image artifacts with optical tapers. It starts with pure geometric aspects caused by the superposition of two periodic structures (the taper and the pixel matrix) of similar but not identical periodicity. As a consequence aliasing will occur (Figure 19, Image A).

Most of the distortions and blemishes visible with optical tapers have their origin in the production process, which involves the flow of softened glass and which, therefore, cannot be controlled in a perfect deterministic way. Common distortions are Shear (Figure 19, Image B1: a straight line at the taper's input appears as a broken line at the output) and Gross (Figure 19, Image B2: a straight line is imaged as a continuously bent line). Spot blemishes include burnt or broken fibers (Figure 20). The immanent structural inhomogeneity of a taper becomes obvious in the so-called chicken wire artifact, which shows the sub-structure of the taper made of many small bundles of fibers fused together. Every contamination (dust, air bubbles, etc.) on the FOP to taper interface and on the taper to sensor interface is perfectly visible on the sensor. In contrast, dust in a contact-less tandem lens system will always stay outside the focal planes of both lenses and cannot affect the image quality.

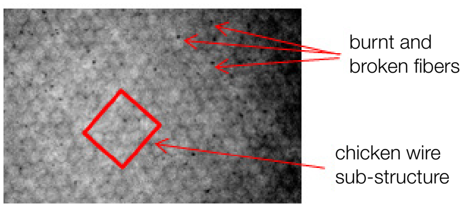
Figure 19: aliasing (Image A), Shear and Gross artifacts of optical tapers (Image B)



Handling, stability, effort and costs

Taper couplings involving optical glue or immersion oil are subject to aging processes. Glued connections between taper and sensor can partially open during the life cycle of a camera system. Air bubbles can intrude into the interface and become clearly visible.

Figure 20: spot blemishes and chicken wire



A definitive advantage of a taper over any high-quality lens coupling is lower cost in addition to size and weight. Whereas a typical taper used in intensified cameras is small (e.g. 25 mm diameter) and lightweight (~ 100 g), an optimized tandem lens system is much larger and heavier (cf. Figure 21).

The manufacturing process for a tandem lens coupled camera system is easier because the imaging method is contactless and both lenses can be focused in the usual way. To bring a taper in direct mechanical contact with the surface of a CCD or sCMOS sensor is a delicate task. In addition, repairs due to the fixed connection with oil or adhesive between taper and sensor are very complicated. Under certain circumstances, these compounds must be chemically dissolved during repair. This will break the sensor. A tandem lens coupled system allows for exchange lenses and sensors in a very flexible and easy way.

In brief:

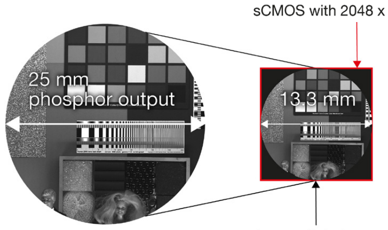
- State-of-the-art tandem lens coupled systems easily achieve, and even outperform, the transmission efficiencies of real taper coupled intensified camera systems.
- Tandem lens systems allow for perfect image quality whereas tapers suffer from various image artifacts caused by their structure and their manufacturing process.
- Taper couplings are significantly smaller and more lightweight than tandem lens systems.
- Tapers have a lower cost factor than high-performance tandem lenses.
- In terms of production process, reliability and ease of maintenance tandem lens systems have a clear advantage against tapered systems.

Figure 21: high end tandem lens system

4 Camera modules

The camera module inside an intensified camera is optically coupled to the phosphor output of the image intensifier. General system parameters like image resolution, frame rate, dynamic range and special functions, such as double image capability, depend on camera module selection. The camera module of the new pco.dicam C1 is based on our cooled sCMOS camera pco.edge 5.5 with CLHS interface. The well-known advantages of sCMOS technology in terms of sensitivity, resolution, speed and dynamic range can be fully exploited to create intensified image data rates far beyond the capabilities of CCD modules. The main engineering challenge of integrating the sCMOS camera module into the pco.dicam C1 is the precise synchronization between image intensifier operation and image acquisition on camera module.

Figure 22: image scaling between phosphor and sCMOS sensor



The size of the image sensor or the effective area selected for capturing the phosphor output dictates the imaging scale that the tandem lens system has to deliver. To deploy the preferred high-resolution image intensifiers with 25 mm diameter and a selected sCMOS sensor area of 2048 x 2048 pixels, the resulting scaling is 13.3 mm : 25 mm = 0.53. Using a 100 mm collimator lens and a 53 mm imaging lens fulfills this requirement.

FORMULA 6

$$\beta = \frac{f_2}{f_1} = \frac{53}{100} = 0.53$$

calculation of imaging scaling for the selected focal lenghts

The projected image circle is completely covered by 2048 x 2048 6.5 µm pixels of the sCMOS detector – cf. Figure 22. There is no waste of valuable intensifier area. As a consequence, the four corners of the sCMOS sensor stay black. For a fast scan of just a few vertically centered lines – the camera module allows for > 7000 fps for such a ROI - the full line length of 2048 pixels is available.

5 Next generation intensified imaging: the new **pco.**dicam C1

5.1 Unmatched image quality through tandem lens coupling

The function, as well as the the advantages, of the newly developed high-performance tandem lens coupling implemented in the new pco.dicam C1 have already been described in chapter 3.

5.2 106 fps @ full resolution

One of the key benefits of using a sCMOS based camera module inside the pco.dicam C1 besides high sensitivity, dynamic and resolution—is the fast frame rate at full pixel resolution. A sustained frame rate of 106 fps at 4.2 MPixel resolution and 16 bit dynamic has turned into reality for the first time with intensified cameras. It is not only the fast sCMOS sensor, it is also the ultra-fast CLHS interface (see below) which has opened the door to an unprecedented intensified image data rate of 880 MByte/s. Partial frame rates scale with their vertical resolution in the sense that reducing the vertical ROI to, for example, 1024 lines result in 212 fps regardless of the horizontal length of these lines.

5.3 Camera Link HS

For the first time, Camera Link HS (CLHS) is used for an intensified camera system. CLHS is the latest interface standard for scientific camera systems. It is specifically designed to meet the needs of vision and imaging applications. It provides low latency, low jitter and real-time signaling between a camera and a frame grabber while transferring large image data rates, control data, and trigger events. The interface builds upon the key strengths of Camera Link by adding new features and functions. Camera Link HS has been developed as an interface that allows sCMOS sensor technology to be fully utilized. The new interface standard for ultimate-performance cameras features:

More bandwidth

- Effective bandwidth of about 1187 MByte/s (CLHS X-Protocol - 10 G) equals roughly three times a USB 3.1 Gen 1 bandwidth & equals the data rate of CoaXPress CXP-12

More robust connection

- A Forward Error Correction algorithm (FEC) ensures no communication error at a Bit Error Rate (BER) of 10^{-12}
- Forward Error Correction corrects burst errors of up to 11 bits on-the-fly
- FEC technology supersedes packet resend mechanism for data reliability
- Fiber Optic Link (FOL) provides high resistance to EMC and allows long cable lengths with the best signal integrity

More distance

- Cable length more than 300 m using multimode fiber
- Cable length more than 10 km with single mode fiber

More flexibility

- Real-time trigger over cable with extremely low jitter
- Plug and Play with GenICam and GenCP
- Using standard LC-connector for flexible cable decision

More open

- The full CLHS specification is downloadable for free
- AIA IP-core is available for fast compliant FPGA implementation (Xilinx, Altera, Lattice)

More cost effective

- The use of standard network hardware components such as enhanced small form-factor pluggable (SFP+) connectors from multiple vendors allows multi sourcing and reduces costs
- Inexpensive licensing

Why FOL interfaces for intensified cameras?

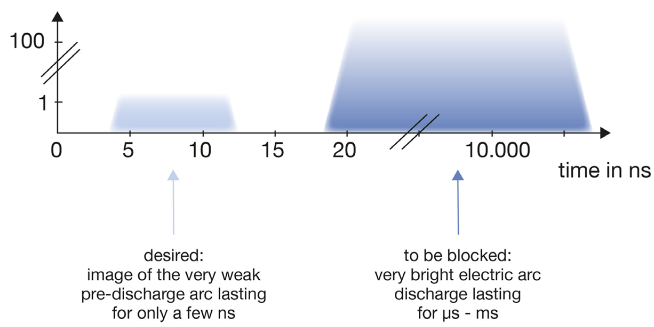
The unique ultra-short gating capabilities of our pco.dicam series cameras are often required in high energy physics. Research facilities working in high energy physics are typically big facilities, housing accelerators, colliders, synchrotrons and FELs. Because of their size, distances between camera control PC and camera location can easily reach several hundred meters, which are best covered with FOL cables. There is no longer the need for deploying electro-optical converter boxes or signal repeaters and add potential sources of error. Additionally, these fiber optical cables are robust against all types of electromagnetic interference. As a common infrastructure, FOL is often already available in high-energy facilities.

5.4 Enhanced extinction ratio gating

A common challenge when working in applications that require image intensification is the huge amount of light which reaches the detector after the end of the configured exposure time, i.e. during readout process of the digital image sensor (sCMOS). If the overall extinction ratio, i.e. the capability of the system to block non-wanted light, is not sufficient, continuous leaking light may outshine the short-termed event.

The simplified example of a very short and weak pre-discharge event which must be captured against the immediately following and long-lasting bright electric discharge may illustrate the situation (Figure 23).

Figure 23: challenging light situation requiring highest extinction ratio



The relation between the length of the configured photocathode exposure and the length of the readout time of the sCMOS detector forces us to be much more concerned with shutter ratios of intensified cameras. Nanosecond exposure times to millisecond readout times define image duty cycles of 10 to the power of -6. To achieve, for example, a signal to noise ratio of 10, the required extinction ratio has to be at least 10^{-7}.

A closer look at the numerical values of the shutter ratio in dependence of the wavelength shows that especially the shorter wavelengths of UV and blue light are less efficiently blocked by the photocathode in close/OFF state (Figure 24).

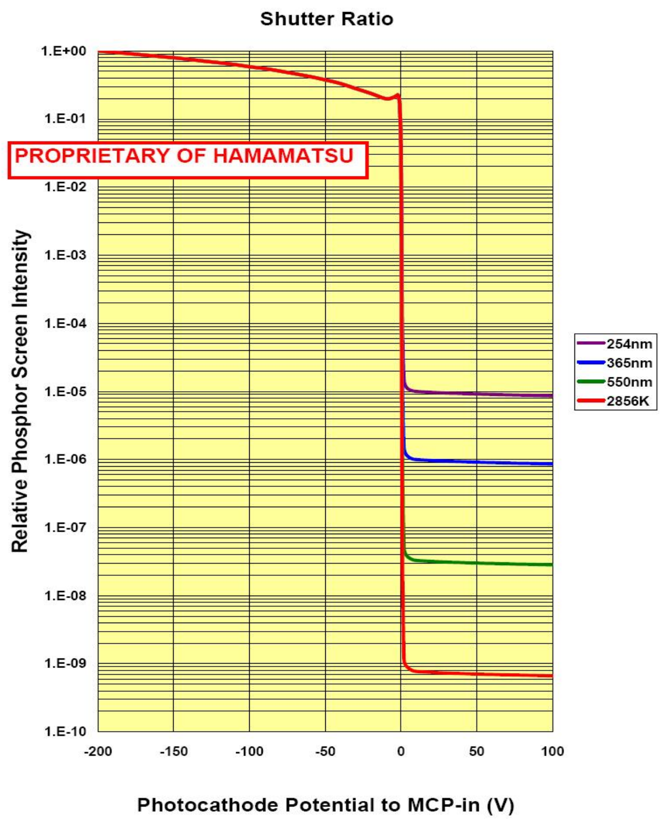
As the photocathode as the main contributor to the overall extinction ratio shows this weakness, it is essential to compensate for that at another point. Hence the new pco.dicam C1 introduces the possibility to do a fast switch off of the micro channel plate bias a few microseconds after the end of the photocathode exposure time. Therefore, photo electrons generated inside the MCP by leaking blue light are not accelerated and multiplied by the MCP anymore. This MCP switch off effectively adds more than two orders of magnitude to the overall extinction ratio with the result that even short wavelength photons reaching the image intensifier outside the photocathode exposure time window encounter an extinction ratio of better than 10^{-7}.

Example

t_{exp} (photocathode) 10 ns, $t_{readout\ sCMOS}$ 10 ms, constant continuous illumination

With the resulting image duty cycle of 1×10^{-6} and an assumed extinction ratio of 1×10^{-8} we would expect only about 1 % of unwanted image content and a SNR of 10^2.

Figure 24: extinction ratio of S20 photocathode material for different wave lengths



Data for S20 photocathode

5.5 Optical trigger and EF lens control

Figure 25: rear view of pco.dicam C1

Figure 26: lens remote controller

In typical experimental environments intensified cameras are often exposed to strong electromagnetic fields. The interference of these fields with trigger signal transmission over copper cable is a very common challenge in those applications. To mitigate the interference, the interface backplane of pco.dicam C1 provides an additional optical trigger input via FOL (Figure 25). Besides being robust against all types of electromagnetic interference, this optical trigger interface allows for the lossless coverage of distances of several hundred meters between trigger source and camera.

Limited access to the camera once it has been installed and is operational also creates the need for a remote control of the optics. For the wide range of Canon EF lenses the pco.dicam C1 offers this option. Remote EF lens control (Figure 26) is integrated into pco.dicam C1's hardware as well as in PCO's proprietary camera control software Camware, which allows for aperture and focus adjustment of an EF lens conveniently from the control PC.