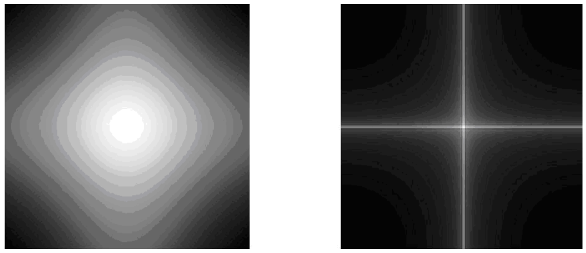


Fig. 7 a) the MTF of the CMOS, b) the PSF of the CMOS

Diffusion MTF decreases with the wavelength. The reason is that the quasi-neutral region is the first region of absorption, and therefore photogenerated carriers due to lower wavelength photons (which are absorbed closer to the surface) experience more diffusion than those generated by higher wavelengths.

2.6 The electrical system analysis

The input signal is projected on the image sensor using the imaging optics. An area image sensor consists of an array of pixels, each containing a photodetector that converts incident light into photocurrent and some of the readout circuits needed to convert the photocurrent into electric charges or voltage and to read it off the array. One of the most popular types of photodetectors are the photodiodes. We use *n+/p-sub* photodiode with very shallow junction depth (section 2.5). The photodiodes are semiconductor devices responsive with capture of photons. They absorb photons and convert them in to electrons. The collected photons increase the voltage across the photodiode, proportional with the incident photon flux. The photodiodes should have goods fill factor and quantum efficiencies [1,4,5,7].

In our paper the CMOS image sensor consists of a $n \times m$, PPS (passive pixels) array. They are based on photodiodes without internal amplification. In these devices each pixel consists of a photodiode and a transistor in order to connect it to a readout structure. Then, after addressing the pixel by opening the row-select transistor, the pixel is reset along the bit line. The readout is performed one row at a time. At the end of integration, charge is read out via the column charge to voltage amplifiers. The amplifiers and the photodiodes in the row are then reset before the next row readout commences. The main advantage of PPS is its small pixel size. In spite of the small pixel size capability and a large fill factor, they suffer from low sensitivity and high noise due to the large column's capacitance with respect to the pixel's one [1,4,5,7].

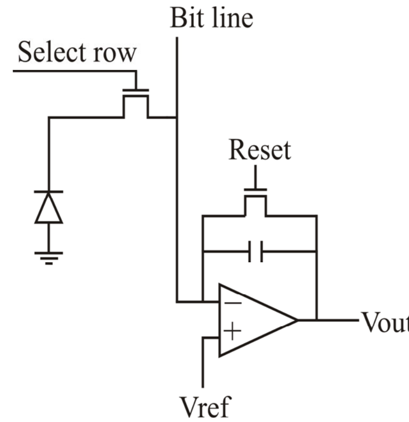


Fig. 8 A schematic of a passive pixel sensor

Photoelectronic noise is due to the statistical nature of light and of the photoelectronic conversion process that take place in image sensors. At low light levels, were the effect is relative severe, photoelectronic noise is often modeled as random with Poisson density function [2,3]. Noises corrupt the utile signals and represent an additive process.

$$N = N_{Poisson} + N_{FPN}. \qquad (32)$$

2.6.1 The photon shot noise

Image noise is a random, usually unwanted, variation in brightness or color information in an image. In a CMOS sensor image noise can originate in electronic noise in the input device sensor and circuitry, or in the unavoidable shot noise of an ideal photon detector. Image noise is most apparent in image regions with low signal level, such as shadow regions or underexposed images. In this paper we focus our attention on the photon shot noise produced by the input captured photons which are transformed in to charges. Shot Noise is associated with the random arrival of photons at any detector. The lower the light levels the smaller the number of photons which reach our detector per unit of time. As a consequence there will not be a continuous illumination but a bombardment by single photons and the image will appear granulose. The signal intensity, i.e. the number of arriving photons per unit of time, is stochastic and can be described by an average value and the appropriate fluctuations. The photon shot noise has the Poisson distribution [2,3,8]

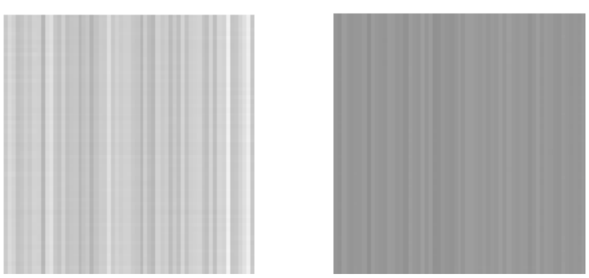
$$P(k, \lambda) = \frac{e^{-\lambda} \lambda^k}{k!} \qquad (33)$$

$k = 1 \div n$, n is a non-negative integer,
λ is a positive real number.
We are interested about photon shot noise effect in the low illuminated image's parts.

2.6.2 The fixed pattern noise

In a CMOS image sensors the noise source can be divided into temporal noises and FPN (Fixed Pattern Noise). In this paper we use only the FPN and do not treat temporal noises. We analyze the FPN specific to CMOS PPS (passive pixel sensor) [1,4,5,7]. In a perfect image sensor, each pixel should have the same output when the same input is applied, but in current image sensors the output of each sensor is different. The FPN is defined as the pixel-to-pixel output variation under uniform illumination due to device and interconnect mismatches across the image sensor array. These variations cause two types of FPN: the offset FPN, which is independent of pixel signal, and the gain FPN or photo response non uniformity, which increases with signal level. Offset FPN is fixed from frame to frame but varies from one sensor array to another. The most serious additional source of FPN is the column FPN introduced by the column amplifiers [1,5,6]. In general PPS has FPN, because PPS has very large operational amplifier offset at each column. Such FPN can cause visually objectionable streaks in the image. Offset FPN caused by the readout devices can be reduced by CDS (correlated double sampling). Each pixel output is readout twice, once right after reset and a second time at the end of the integration. The sample after reset is then subtracted from the one after integration.

For a more detailed explanation, check out the paper by Abbas El Gammal that is listed in the reference section [6]. In this paper we focus our attention in FPN effects on image quality and we do not compute the FPN, we accept the noises as they are presented in references [6].



a b

Fig. 9 PPS FPN a) PPS FPN without CDS, b) PPS FPN with CDS

2.6.3 The analog to digital conversion

The analog to digital conversion is the last block of the analog signal processing circuits in the CMOS image sensor. In order to convert the analog signal in to digital signal we compute the: analog to digital curve, the voltage swing and the number of bits. The quality of the converted image is good and the image seams to be unaffected by the conversion [1,4,5].

3 The image reconstruction

At the output of the optical part the image is blurred as a result of its propagation trough the optical system and also present shape's deformations due to aberrations. In order to recover the image resolution we need to sharp the image [2,3,8], using a Laplacian filter. At the output of the electrical part the image is corrupted by the combined noise. In order to reduce the FPN we use a frequencies amplitude filter to block the spikes spectrum of the FPN, and also we use a bilateral filter in order to reduce the photon shot noise [16,17].

3.1 The image sharpening

In order to correct the blur and to preserve the impression of depth, clarity and fine details we have to sharp the image using a Laplacian filter [2,3,8]. A Laplace filter is a 3x3 pixel mask

$$L = \begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix} \tag{34}$$

In order to restore the blurred image we subtract the Laplacian image from the original image.

3.2 The amplitude filter

The FPN is introduced by the sensor's column amplifiers and consists of vertical stripes with different amplitudes and periods. Such type of noise in the Fourier plane produces a set of spikes periodic orientate. A procedure to remove this kind of noise is to make a transmittance mask in Fourier 2D logarithm plane. The first step is to block the principal components of the noise pattern. This block can be done by placing a band stop filter $H(u,v)$ in the location of each spike [8,12,13,16]. If $H(u,v)$ is constructed to block only components associated with the noise pattern, it fallows that the Fourier transform of the pattern is given by the relation [16]:

$$P(u,v) = H(u,v)\log[G(u,v)] \tag{35}$$

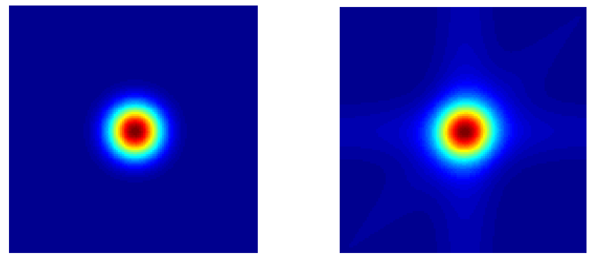
where $G(u,v)$ is Fourier transform of the corrupted image $g(x,y)$.

After a particular filter has been set, the corresponding pattern in the spatial domain is obtained making the inverse Fourier transform:

$$p(x,y) = F\{\exp[P(u,v)]\}. \tag{36}$$

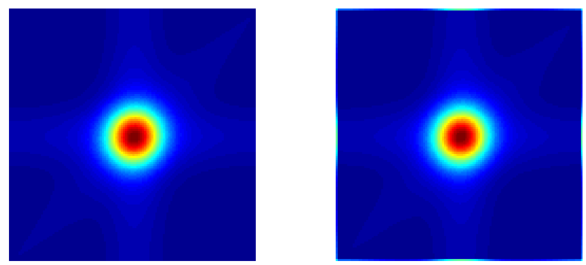
3.3 The bilateral filter
In order to reduce the random noise effect we use a bilateral filter. It extends the concept of Gaussian smoothing by weighting the filter coefficients with their corresponding relative pixel intensities. Pixels that are very different in intensity from the central pixel are weighted less even though they may be in close proximity to the central pixel. This is effectively a convolution with a non-linear Gaussian filter, with weights based on pixel intensities. This is applied as two Gaussian filters at a localized pixel neighborhood, one in the spatial domain, named the domain filter, and one in the intensity domain, named the range filter [17].

4 The simulation results
In this paper we imagine the TEM_{00} laser pulse propagation trough the proposed image acquisition system. We assume that we have a confocal resonator which generates the Gaussian pulse. In order not to spread too much we focus the pulse (Fig. 10, a)), in to a graded index fiber using a lens (Fig. 10, b)). Due to the fiber characteristics, the Gaussian spatial confining of the light wave is preserved as the light propagates through the fiber. Consequently the fiber preserves the spatial resolution of the original Gaussian pulse. At the output of the fiber the radiation is projected on a CMOS image acquisition sensor. The sensor has an optical part which is characterized by its PSF; the output image can be seen in Fig. 11 a). At the end of the optical part we use the Laplace sharpening filter in order to correct the blur of the Gaussian pulse (Fig. 11, b)), which was produced during the radiation propagation trough the optical system. We are interest to preserve the pulse shape during its propagation trough the system and for our purpose a black and white analysis should be enough. Consequently we can use a sensor that don't Bayer sample and interpolate the input signal and also the signal luminosity is considered to be good enough. Having those aspects set, we focus our attention to the noises. We simulate the photon shot noise and the FPN afferent to a CMOS PPS, and the noises combination represent an additive process (Fig. 12, a)). Finally the analog signal is converted into digital signal. During the signal propagation through the electrical part of the CMOS sensor, its characteristics are degraded by noises. In order to recover the image characteristics we use an amplitude filter and a bilateral filter (Fig. 12, b)). To better understand the simulation effect, in Fig. 13 we have a 3D spatial representation of the original image and the recovered image. Due to the modest quality of the lens, we see that the final image (Fig. 13 b)) is degraded by the aberrations. As a consequence of this fact the pulse is a little attenuated in amplitude and widen at the base. The noises can be rejected by the proposed filters' combination.



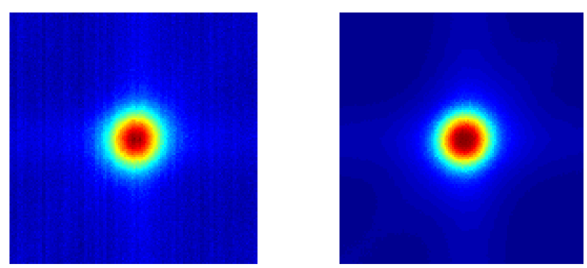
a b

Fig. 10 a) the Gaussian pulse, b) the Gaussian pulse at the lens output



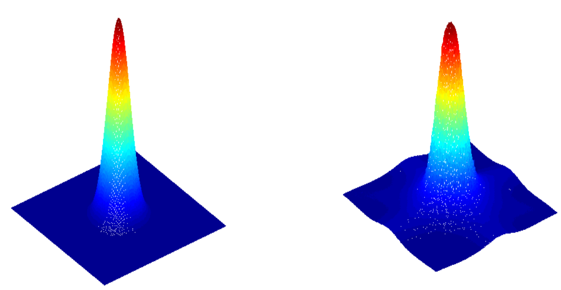
a b

Fig. 11 a) the Gaussian pulse at the output of the CMOS optical part, b) the sharp image



a b

Fig. 12 a) the noisy image at the output of the electrical part, b) the recovered image



a b

Fig. 13 a) the original pulse, b) the recovered pulse

Conclusions

In this paper we simulate the TEM_{00} confocal laser pulse propagation trough an image acquisition system. We simulated the image characteristics at the output of each block from our system configuration. The purpose of this paper was to put to work together, in the same system, optical and electrical components and to recover the degraded signal. The simulation algorithm works in real time; many other configurations can be done using other different optical and electrical components. Also we can combine in different ways the aberrations and noises obtaining other simulations which can be done using our proposed image capture system.

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