Simulation the functionality of a laser pulse image acquisition system

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Abstract: - The goal of this paper is to generate a laser pulse and to capture it by an image acquisition system. We use a confocal resonator to generate a laser pulse; then the generate light is focused in to an optical fiber using a lens; the light propagates through the fiber and at the fiber output light is projected on a CMOS sensor. We compute the PSF (point spread function) and MTF (modulation transfer function) in order to characterize the functionality of the lens and the optical part of a CMOS sensor. We analyze the CMOS electrical part considering the photon shot noise and the FPN (fixed pattern noise). Finally, we use a Lapacian filter, an amplitude filter and a bilateral filter in order to reconstruct the noisy blurred image. We consider the image capture system to be linear shift invariant, axial and the light is orthogonal to the system.

Key-Words: - Hermite Gaussian polynomial, lens design, PSF, MTF, fixed pattern noise, photon shot noise, amplitude filter, Laplacian filter, bilateral filter

1 Introduction

Image acquisition sensors are complex systems of optical, mechanical and electrical components, which convert radiance into numerical signals [4,7]. Consequently, they require to transform the signals through a number of different devices. Our system consists of a laser whose functionality is characterized by the Hermite Gaussian polynomial, a graded index fiber, a lens, a CMOS sensor, a Lapacian filter, an amplitude filter and a bilateral filter. In this simulation we shall try to imagine the functionality of the system when a Hermite Gaussian pulse propagates trough it. We focus our analysis to the aspects related to system resolution, noises analysis and the signal recovery.

Due to the signal transformations that happen during the pulse propagations trough the devices from which is made our image acquisition system, we need a controlled simulation in order to better understand the system functionality. We control the simulation environment in order to provide the engineer with useful guidance that improves the understanding of design considerations for individual parts and algorithms.

We consider the image capture system to be LSI (linear shift invariant) [4,9,16], axial and the light is

orthogonal to the system. We assume that we have a spherical mirror resonant cavity which generates the Hermite Gaussian paraxial beam. The Gaussian beam remains a Gaussian beam as long as the overall system maintains the paraxial nature of the wave [13]. Consequently, we have to ensure this condition and we focus the pulse, with a lens, set at z = 20mm in front of the resonator, in to a fiber.

During the Gaussian pulse propagation trough the image capture system the useful signal become noisy and blurred. In order to reconstruct the signal we sharp and we filter the noises.

2 The image capture system

The image capture system can be divided in two parts: the optical part and the electrical part. The optical system must be axial.

2.1 The resonator modes

In order to find the laser modes we consider a confocal resonator system. The optical axis is noted with z, and the light propagates from left to right in report with the optical axis. The resonator is made by two concave mirrors of equal radii of curvature

 $R = \frac{d}{2}$ separated by a distance *d*, and one mirror is a partially refractive mirror M_2 [13]. We consider the middle of the resonator in the point $z = -\frac{d}{2} + \frac{d}{2} = 0$.



Fig. 1 A schematic of the image capture system

After certain calculus [12], the modes in the middle of the resonator can be express as

$$\psi(x, y, z = 0) = E_0 \exp\left[-\frac{\left(x^2 + y^2\right)}{w_0^2}\right]$$

$$H_m\left(\frac{\sqrt{2}x}{w_0}\right)H_n\left(\frac{\sqrt{2}y}{w_0}\right)$$
(1)

where w_0 is the waist of the beam, H_m is the Hermite Gaussian polynomials

$$H_m(x) = (-1)^m e^{x^2} \frac{d^m}{dx^m} e^{-x^2}.$$
 (2)



Fig. 2 The Hermite Gaussian intensity distribution in transverse plane a) TEM_{00} , b) TEM_{11} , c) TEM_{12}

Each set (m,n) corresponds to a particular transverse electromagnetic mode of the resonator as the electric (and magnetic) field of the electromagnetic wave is orthogonal in the middle of the resonator in point z = 0. The lowest-order Hermite polynomial H_0 is equal to unity; hence the mode corresponding to the set (0,0) is called the TEM_{00} mode and has a Gaussian radial profile. The laser output comprises a small fraction of the energy in the resonator that is coupled out through a partially refractive mirror. The width of the Gaussian beam is a monotonically increasing function of propagation on direction z, and reaches $\sqrt{2}$ times its original width at Rayleigh range. For a circular beam, this means that the mode area is doubled at this point [12,13].

In this paper we consider that the laser generates a pulse with a Gaussian radial profile (TEM_{00}) . In order not to spread too much its width, in the Rayleigh range at 20mm, we focus the pulse in to a graded index fiber using a lens.

2.2 The optical system analysis

When we work with optical components, the most important problem is that it is impossible to image a point object as a perfect point image. An optical system is made by a set of components (surfaces) through which the light passes. The optical sensor is analyzed in space by the PSF (point spread function) and in the spatial frequency by the MTF (modulation transfer function), which are the most important integrative criterions of imaging evaluation for the optical system [3,4,9,10,16]. The PSF gives the 2D intensity distribution about the image of a point source. PSF gives the physically correct light distribution in the image plane including the effects of aberrations and diffraction. Errors are introduced by design (geometrical aberrations), optical and mechanical fabrication or alignment. MTF characterize the optical system functionality in spatial frequencies. Most optical systems are expected to perform a predetermined level of image integrity. A method to measure this quality level is the ability of the optical system to transfer various levels of details from the object to the image. This performance is measured in terms of contrast or modulation, and is related to the degradation of the image of a perfect source produced by a lens. MTF describe the image structure as a function of spatial frequency and is specified in lines per millimeter. It is obtain by Fourier transform in the image spatial distribution or spread function.

When an optical system process an image using incoherent light, then the function which describe the intensity in the image plane produced by a point in the object plane is called the impulse response function [3,4,9,10,16]:

$$g(x, y) = H[f(x, y)]$$
(3)

H is an operator representing a linear, position (or space) invariant system. The input object intensity pattern and the output image intensity pattern are related by a simple convolution equation:

$$g(x, y) = \int_{-\infty}^{+\infty} f(\alpha, \beta) H[\delta((x - \alpha, y - \beta))] d\alpha d\beta$$

$$g(x, y) = \int_{-\infty}^{+\infty} f(\alpha, \beta) h(x - \alpha, y - \beta) d\alpha d\beta \qquad (4)$$

 $h(x - \alpha, y - \beta) = H[\delta(x - \alpha, y - \beta)]$ is the impulse response of *H*; in optics, it is called the point spread function (PSF) [3,4,9,10,16].

The image acquisition sensor's PSF is a multiple convolution of individual response from each optical component trough which the light propagates: the lens and the transfer function of the CMOS [14,15]

$$PSF = PSF_{lens} * PSF_{CMOS}.$$
 (5)

The PSF characterizes the image analyses in space but also we can characterize the image in frequency using the OTF (optical transfer function). OTF is the normalized autocorrelation of the transfer function and has the formula:

$$H(\alpha,\beta) = \frac{\iint P(u+\frac{\alpha}{2},v+\frac{\beta}{2})P(u-\frac{\alpha}{2},v-\frac{\beta}{2})dxdy}{\iint P(u,v)^2 dxdy}$$
(6)

The numerator represents the area of overlap of two pupil functions P (square or circle), one of which is

displaced by $\frac{\alpha}{2}$ in direction *u* and by $\frac{\beta}{2}$ in direction

v; and the other in opposite direction by $-\frac{\alpha}{2}$ and -

 $\frac{\beta}{2}$. The denominator represents the complete area

of the pupil function [3,4,9,16].

The change in contrast when an image passes trough an optical system is expected to have a lot to do with the optical transfer function that specifies the quality of the system.

The MTF (modulation transfer function) is defined as: the ratio of the contrast of the output image to that of the input image

$$MTF = \frac{contrast \quad of \quad output \quad image}{contrast \quad of \quad input \quad image}.$$

The OTF describe the response of the optical system to a know input and the relation between OTF and MTF is:

$$MTF = |OTF|. \tag{7}$$

In conclusion, the modulation transfer function is identical to the absolute value of the optical transfer function. The net sensor's MTF is a multiplication of individual transfer functions in a way similar to equation 5.

$$MTF = MTF_{lens} \cdot MTF_{CMOS} \tag{8}$$

In general, the contrast of any image which has gone through an image capture system is worse that the contrast of the input image. The PSF afferent to the sensor's optical part is a convolution of individual response from the lens and the optical part of the CMOS sensor [14,15]. We work with multiple convolutions, and we focus our attention on space analysis using PSF specific to each device from the optical sensor. The optical fiber is analyzed from the spatial resolution point of view.

2.3 The lens design

Optical lens design refers to the calculation of lens construction parameters that will meet a set of constraints. performance requirements and Construction parameters include surface profile types and the parameters such as radius of curvature, thickness, semi diameter, glass type and optionally tilt and decenter [4]. In our particularly case we design a lens with power and coma x errors [10]. Before we proceed, we notice that the human eye can only distinguish aberrations up to the fourth or fifth order. When we design the lens we have to take in consideration the: aberrations, the aberration correction and the design consideration [18].

2.3.1. The monochromatic aberrations

Aberrations are the failure of light rays emerging from a point object to form a perfect point image after passing through an optical system. Aberrations lead to blurring of the image, which is produced by the image-forming optical system [4,10,18]. The wave front emerging from a real lens is complex because has error in the design, fabrication and lens assembly. Nevertheless, well made and carefully assembled lenses possess certain inherent aberrations. To describe the primary monochromatic aberrations, of rotationally symmetrical optical systems, we specify the shape of the wave front emerging from the exit pupil. For each object point, there will be a quasi-spherical wave front converging toward the paraxial image point.



Fig. 3 The wavefront aberrations

The wave aberration function, W(x,y), is defined as the distance, in optical path length, from the reference sphere to the wavefront in the exit pupil measured along the ray as a function of the transverse coordinates (x,y) of the ray intersection with a reference sphere centered on the ideal image point [4,10,18].

To specifies the aberrations we use the Siedel field aberration formula:

$$W(r,\theta) = W_{020}r^{2} + W_{040}r^{4} + W_{131}hr^{3}\cos(\theta) + W_{220}h^{2}r^{2} + W_{311}h^{3}r\cos(\theta) +$$
(9)
(higher order terms)

 W_{klm} are the wave aberration coefficients for the various terms of modes, *h* is the height of the object and r, θ are the polar coordinate in the pupil plane,

r^2	Defocus,
r^4	Spherical Aberration,
$hr^3\cos(\theta)$	Coma,
$h^2 r^2 \cos^2(\theta)$	Astigmatism,
h^2r^2	Field Curvature,
$h^3 r \cos(\theta)$	Distortion.

These Seidel aberrations formula represents orthogonal polynomials which have the next properties: field aberrations describe the wavefront for a single object point as a function of pupil coordinates (x,y) and field height h. The aberrations are described functionally as a linear combination of polynomials. Point aberrations depend only on pupil coordinates and each polynomial term represents a single aberration. The aberration polynomial may be extended to higher order; these are all the terms to fourth order. Ray aberrations are described by a polynomial one order lower than the corresponding wave aberrations [4,10,18].

The design variables are the two surface curvatures. The defect functions [10] are power and coma. The wavefront errors introduced are given by power W_{020} and coma W_{131}

$$W_{020} = \frac{1}{2\lambda} y_a^2 \frac{\phi}{V}$$
(10)

$$W_{131} = \frac{1}{4\lambda} y_a^2 \phi^2 L(a_5 B - a_6 M)$$
(11)

 λ - the wave length,

 y_a - the aperture,

 ϕ - the lens power,

V - the Abbe number,

 $L = -nu_a y_c \text{ - the Lagrange invariant,}$ $B = \frac{c_1 + c_2}{c_1 - c_2} \text{ - the bending,}$

 n_g is the glass refraction indices,

$$M = \frac{1+m}{1-m}$$
 is the magnification,
$$a_5 = \frac{n_g + 1}{n_g (n_g - 1)}, \ a_6 = \frac{2n_g + 1}{n_g}.$$

2.3.2 Aberrations correction

We have the mathematical relation that describes the optical design which implies Seidel aberrations [4, 10,18]. The defect vector f is a set of m functions f_i that depend on a set on n variables. The function is of the type:

$$\sigma^2 = f^t \cdot f \tag{12}$$

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A is a $(n \times m)$ matrix of first derivatives:

$$A_{ij} = \frac{\partial f_i}{\partial x_i}$$

and s are changes in the variables from the current design. The gradient g is a $(n \times 1)$ vector given by:

$$g = \frac{1}{2} \nabla \sigma^2 \tag{13}$$

its components are:

$$g_{i} = \frac{\partial \sigma^{2}}{\partial x_{i}} = 2 \left(f_{1} \frac{\partial f_{1}}{\partial x_{i}} + f_{2} \frac{\partial f_{2}}{\partial x_{i}} + \dots f_{m} \frac{\partial f_{m}}{\partial x_{i}} \right)$$
$$g = A^{t} f . \tag{14}$$

Method of Least Squares

$$g = A^{t} (f_{0} + As)$$
$$g = g_{0} + A^{t} As$$
$$C = A^{t} A$$
$$g_{0} + Cs = 0$$

is a set of simultaneous linear equations known as the normal equations of least-squares. Providing that the matrix C is not singular, these equations can always be solved, and the formal solution s may be written:

$$s = -C^{-1}g_0.$$
 (15)

The basic idea of the damped least-squares is to start with the basic equation for the least squares condition. g_0 is the gradient at the starting point and augment the diagonal of the matrix *C* by the addition or factoring of a damping coefficient. Modifications of the form $c_{ii} + p$ for example, are called additive damping [10]. In the case of additive damping, the equation for the damped least-squares solution reduces to:

$$g_0 + ps + Cs = 0. (16)$$

As the damping factor p increases, the third term in

the equation above becomes small and the solution vector becomes parallel to the gradient vector.

$$s = -\frac{1}{p}g_0. \tag{17}$$

2.3.3 Calculus example

Make the lens focal length 20mm with an f/2 aperture ($y_a = 5mm$). Let the half field angle u_c be 0.1 (5.73°) and the wavelength be 0.55µm. Let the glass index of refraction n_g be 1.5 and we assume the object is at infinity (M = 1). To solve this problem we must solve the equation system:

$$\begin{cases} f_1 = \phi - \phi_1 \\ f_2 = \frac{1}{2} \phi^2 L(a_5 B - a_6 M) \end{cases}$$

Fig. 4 The lens design, a) the MTF on Cartesian scale, b) the PSF on logarithmic scale

2.4 The graded index fiber

During the radiation propagation trough the optical fiber it supports two types of dispersions: material dispersion and modal dispersion. Happily, due to type of fiber that we use the modal dispersion is not important. A graded-index fiber is an optical fiber whose core has a refractive index that decreases with increasing radial distance from the fiber axis [9,12,13]. The index profile is very nearly parabolic. The advantage of the graded-index is the considerable decrease in modal dispersion ensuring a constant propagation velocity for all light rays

We are interested to see what happens to a pulse that propagates trough a graded index fiber [9,12]. We use the beam propagation method and we assume the graded index medium has a refractive index variation of the form [9,12]:

$$n(x, y) = n_0 [1 + \Delta(x, y)].$$
 (18)

 n_0 is the intrinsic refractive index of the medium, n(x,y) is the medium index of refraction in the location (x,y),

 $\Delta(x, y)$ is the variation of n(x, y).

In reference [12] is presented a beautiful demonstration in which a plane wave propagates trough a graded index fiber. After the plane wave is substitute in the wave equation, the equation is solved and the results are the Hermite Gaussian polynomials. Since we have total mathematical compatibility the only concern should be related to propagation to the refractive index. Due to the periodic focusing by the graded index distribution the Gaussian pulse does not deform as it propagates through the fiber. This means that the Gaussian spatial confining of the light wave is preserved as the light propagates through the fiber. So the fiber preserves the spatial resolution of the original Gaussian pulse. At the output of the fiber the light is projected on the CMOS.

2.5 The CMOS MTF

The sharpness of a photographic imaging system or of a component of the system (the lens and the optical part of CMOS) is characterized by the MTF, also known as spatial frequency response. The CMOS optical part is characterized by its afferent MTF. The contrast in an image can be characterized by the modulation [4,7,14,15]

$$M = \frac{s_{\max} - s_{\min}}{s_{\max} + s_{\min}}$$
(19)

where s_{max} and s_{min} are the maximum and minimum pixel values over the image. Note that: $0 \le M \le 1$.

Let the input signal to an image sensor be a 1D sinusoidal monochromatic photon flux:

$$F(x, f) = F_0 [1 + \cos(2\pi f x)]$$
(20)

for $0 \le f \le f_{Nyquist}$.

The sensor modulation transfer function is defined as:

$$MTF(f) = \frac{M_{out}(f)}{M_{in}(f)}$$
(21)

from the definition of the input signal, $M_{in} = 1$. MTF is difficult to find analytically and is typically determined experimentally. For the beginning we made a 1D analysis for simplicity and at the end we generalize the results to 2D model, which we will use in our analyses.

By making several simplifying assumptions, the sensor can be modeled as a 1D linear space-invariant system with impulse response h(x) that is real, nonnegative, and even. In this case the transfer function:

$$H(f) = F[h(x)] \tag{22}$$

is real and even, and the signal at *x* is:

$$S(x) = F(x, f) * h(x)$$

$$S(x) = F_0 [1 + \cos(2\pi f x)] * h(x)$$

$$S(x) = F_0 [H(0) + H(f)\cos(2\pi f x)]$$
(23)

therefore:

$$S_{\max} = F_0 [H(0) + |H(f)]]$$

$$S_{\min} = F_0 [H(0) - |H(f)]]$$

and the sensor MTF is given by:

$$MTF(f) = \frac{|H(f)|}{H(0)}$$
(24)

We consider a 1-D doubly infinite image sensor.



L- quasi neutral region

 L_d - depletion depth

w- aperture length

p- pixel size

To model the sensor's response as a linear spaceinvariant system, we assume n+/p-sub photodiode with very shallow junction depth, and therefore we can neglect generation in the isolated n+ regions and only consider generation in the depletion and p-type quasi-neutral regions. We assume a uniform depletion region (from $-\infty$ to ∞) [4,7]. The monochromatic input photon flux F(x) to the pixel current iph(x) can be represented by the linear space invariant system (Fig. 6). iph(x) is sampled at regular intervals p to get the pixels photocurrents.



$$r\left(\frac{x}{w}\right) = \begin{cases} 1 & |x| \le \frac{w}{2} \\ 0 & otherwise \end{cases}$$
(25)

d(x) is the (spatial) impulse response corresponding to the conversion from photon flux to photocurrent density, and we assume a square photodetector. The impulse response of the system is thus given by its Fourier transform (transfer function) [14,15]

 $I \rightarrow$

$$h(x) = d(x) * \omega r\left(\frac{x}{\omega}\right)$$
(26)

and its Fourier transform (transfer function) is given by:

$$H(f) = D(f)\omega^2 \sin c(\omega f)$$
(27)

note that: $D(0) = n(\lambda),$

 $n(\lambda)$ - spectral response.

By definition: the spectral response is a fraction of photon flux that contributes to photocurrents as a function of wave length. So D(f) can be viewed as a generalized spectral response (function of spatial frequency as well as wavelength).

After some calculus we get D(f) as:

$$D(f) = \frac{q(1 + \alpha L_f - e^{\alpha L_d})}{1 + \alpha L_f} - \frac{qL_f \alpha e^{\alpha L_d} \left(e^{\alpha L} - e^{\frac{L}{L_f}}\right)}{\left(1 - (\alpha L_f)^2\right) \sinh\left(\frac{L}{L_f}\right)}$$
$$H(f) = D(f) w^2 \sin c(wf)$$
(28)

the modulation transfer functions for $|f| \le \frac{1}{2n}$ is:

$$MTF(f) = \frac{|H(f)|}{H(0)} = \frac{D_f}{D_0} w^2 \sin c(wf)$$
(29)

 $\frac{D_f}{D_0}$ is called the diffusion MTF and $\sin c(wf)$ is

called the geometric MTF.

Consequently, we have:

MTF

$$MTF_{CMOS} = MTF_{diffusin} \cdot MTF_{geometric}$$
(30)

But in our analyses we use 2D signals (image) so we must generalize 1D case to 2D case. We know that we have square aperture at each photodiode with length w; so the analyses is made in Cartesian coordinate and we must generalize in x-y coordinate MTF(f) and we have:

$$MTF(f_x, f_y) = \frac{|H(f_x, f_y)|}{H(0)}$$
(31)
$$(f_x, f_y) = \frac{D_{(f_x, f_y)}}{D_0} w^2 \sin c(wf_x) \sin c(wf_y)$$

 f_x - spatial frequency on x direction

 f_{y} - spatial frequency on y direction

Spatial frequency (lines/mm) is defined as the rate of repetition of a particular pattern in unit distance. It is indispensable in quantitatively describing the resolution power of a lens. The first level in a CMOS image sensor is a lens which focuses the light on each pixel photodiode.



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.

$$N = N_{Poisson} + N_{FPN}.$$
 (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]

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



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

$$L = \begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$
(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]:

$$P(u,v) = H(u,v)\log[G(u,v)]$$
(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:

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



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





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





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



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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