A Study of the Performance of an InGaAs CCD Linear Photodiode Array for Fiber-Optic Grating Sensors

Plamen Balzhiev[1], Rumen Arnaudov[2] and Tinko Eftimov[3]

Abstract – **The paper covers the experimental set-ups, the measurement algorithms, as well as the processing and analysis of results in order to obtain certain optical characteristics of an InGaAs CCD linear photodiode array such as noise levels, dynamic range, linearity response, tolerances of pixel parameters.**

Keywords – **Fiber-optic grating sensors, InGaAs photodiode, CCD image array.**

I. INTRODUCTION

Fiber optic grating sensing technology has witnessed a fast growth during the last decade because of its inherent capability to multiplex spectrally a large number of both fiber Bragg gratings (FBGs) and long period gratings (LPGs). This attractive opportunity demands sophisticated sensor interrogation devices [1]. One of the most popular techniques is the use of InGaAs CCD photodiode arrays, sensitive in the near infrared region from 800 nm to 1750 nm where most of the fiber gratings' spectra are situated. Since fiber gratings' transmission minima may be very deep – up to 30 dB, and the grating may also be spectrally very narrow (tens of picometers) it essential to determine the parameters of the CCD array and the whole electronic unit for the proper design of the fiber grating interrogation system. The basic characteristics related to their use in these particular applications and which we study in this paper are noise levels, dynamic range, linearity of response, sensitivity.

The accuracy of the measurement crucially depends on the choice of the operating point of the detection unit. Because of the specific applications where high dynamic range is needed for low level signals at grating resonance wavelength, the catalogue data are not sufficient for the proper design of the interrogation unit.

The paper covers the description of the interrogation measurement system, the experimental set-ups, the measurement algorithms, as well as the processing and analysis of results. The interrogation unit thus developed and tested can be used not only for fiber grating interrogation, but for other spectrally encoded fiber sensors in the 800 nm – 1750 nm range, such as SPR (surface plasmon resonance), polarimetric and interferometric sensors [2] with spectrally resolved detection connected in a larger fiber optic sensing network.

II. FIBER GRATING INTERROGATION SYSTEM

A. System description

The optoelectronic measurement system is designed to investigate measure and analyze fiber-optic sensors using spectrally multiplexed fiber gratings. This particular system presented on Fig 1 is employed for the experimental measurement and test of the CCD array. It consists of a broadband amplified spontaneous emission (ASE) light source (Joinwit), that emits in the conventional and long-wavelength (*C* + *L*) communication band from 1525 nm to 1605 nm, an optical fiber, a fiber-optic attenuator, a collimating lens system, a diffraction grating of 600 lines/mm, the CCD photodiode array under study and the associated electronic unit. The latter transform the incident light into digital data which is further transmitted to a personal computer for processing, analysis and visualization.

The optoelectronic unit is specially designed as a part of grating interrogation system. The block diagram of the measurement device (Fig 2) consists of CCD array – G9204-512D (manufactured by Hamamatsu Photonics). It is a 512

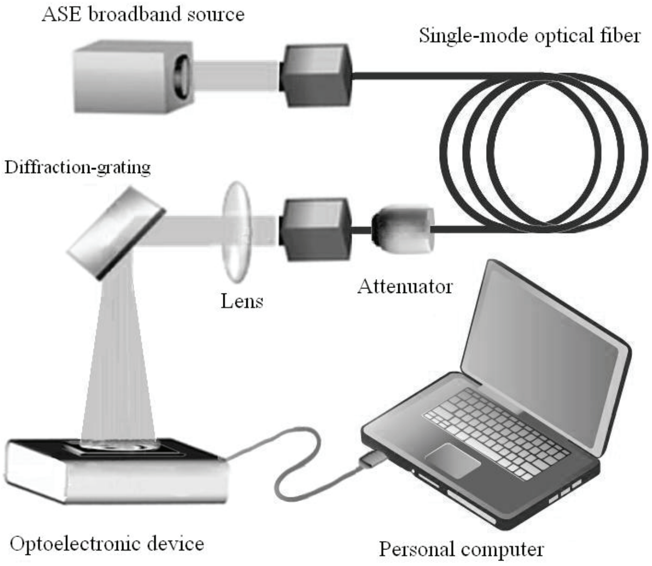

Fig. 1. Diagram of grating interrogation system

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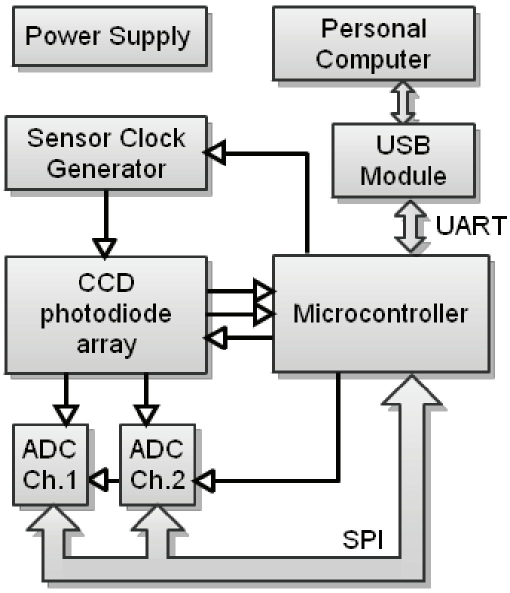

Fig. 2. Block diagram of optoelectronic device

pixel linear InGaAs photodiode array with high sensitivity and stability in 800-1750nm spectral range, low dark current and integrated low noise charge amplifier array comprised of CMOS transistors. Two high-speed capacitive-based SAR analog-digital converters (ADC) transform the analog data from the CCD sensor into 16-bit corresponding digital values. A programmable pulse generator (up to 4MHz) provides the needed clock signals for the proper operation of CCD photodiode array.

The microcontroller in this device performs a set-up of the CCD sensor and ADCs and conducts the measurement procedure [5]. It forms all necessary signals for each individual module to provide accuracy and proper measurement. The obtained data is further transmitted via USB interface to a personal computer. For this purpose serial UART interface to USB converting device is implemented which provides flexibility and high data rates. The designed power supply unit is based on the LDO regulators that produce a low ripple output voltage of 5V and low noise reference voltages of 4,5V and 1,26V for the CCD photodiode array. Some major parameters of the optoelectronic measurement device as part of a grating interrogation system are provided in Table1.

TABLE I
OPTOELECTRONIC DEVICE PARAMETERS

Parameter	Value
Sensor (pixel number)	512
Pixel frequency	500 kHz (up to 4MHz)
Integration time	1ms - 100ms
Pixel Readout time, ms	8,4 ms
ADC Resolution	16 bit
ADC Convertion Rate	500 kSps
ADC Non-linearity, LSB	< ±3
USB transfer speed	500 kbps (up to 2Mbps)
Power consumption(typical @5V)	280mA

B. Measurement algorithm

The optoelectronic device conducts the measurement of all 512 pixels from CCD photodiode array. The operation algorithm presented in Fig. 3 starts with a preliminary initialization of all modules which is followed by configuration and measurement set-up according to previously assigned values from the computer [5]. The parameters that are manually set up are integration time (τ), sensor sensitivity (s), conversion speed and data communication speed (r). The measurement process is performed as the device consecutively reads values from the photodiode array which are converted into 16-bit digital values. After reading all pixels data is further transmitted to a personal computer for processing and visualization.

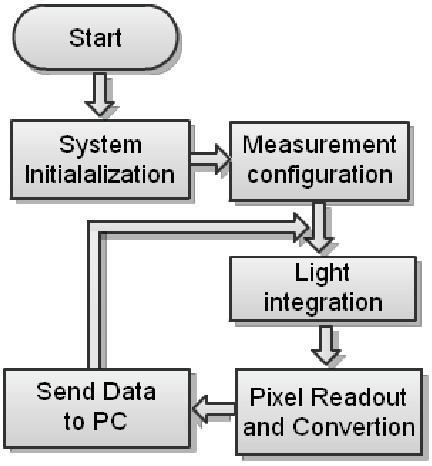

Fig. 3. Block diagram of optoelectronic device

C. Processing and analysis of results

Data processing algorithms are implemented into the personal computer. A dark current measurement procedure is initially conducted. This data includes the minimal values of measurement process as well as photon and read noise of the CCD sensor, additional sampling noise from ADC and the system noise added from the power supply. This data is necessary to suppress unwanted oscillations. To obtain a reliable and accurate assessment of the dark values an averaging of N-measurements is implemented (1) [4].

$$\hat{S}_d(n) = \frac{1}{N}\sum_{k=0}^{N} S_k(n) \qquad (1)$$

The further conducted measurements are presented as relative values to the dark measurement values. In order to avoid high frequency oscillations a low pass filter is applied and the final representative data is obtained from formula (2).

$$\hat{S}(n) = \frac{1}{M}\sum_{m=0}^{M}(S_m(n) - \hat{S}_d(n)) \qquad (2)$$

III. PERFORMANCE OF INGAAS CCD LINEAR PHOTODIODE ARRAY

The measurements of the noise levels, the dynamic range and linearity characteristics of the 512 pixel CCD photodiode array were conducted in laboratory conditions with the above described interrogation system. The CCD sensor is tested with the ASE light source and calibrated output power. The minimum total optical power in the 1525-1605 nm range was 9 nW. On Fig.4 the not calibrated spectrum of broadband ASE light source is presented which is measured with the same interrogation system.

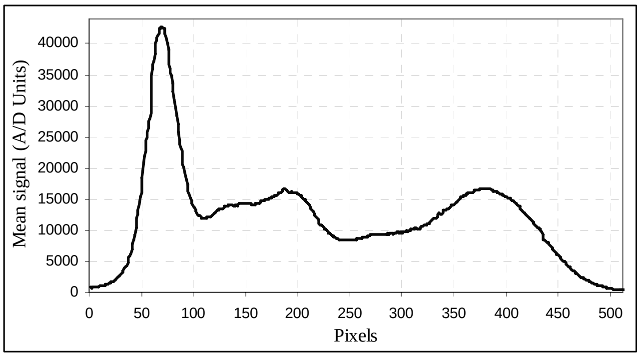

Fig. 4. Measured spectrum of the ASE broad-band (1525-1605 nm) source

A. Noise Levels

The measured noise levels of CCD sensor comprise from many sources – photon noise, dark noise and read noise. Noise levels are calculated as a deviation from the average signal levels (3) [4].

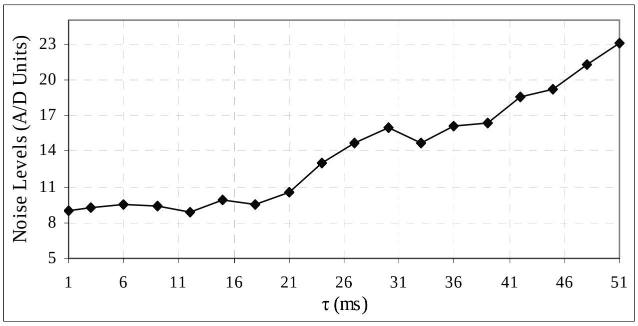

Fig. 5. Noise levels of CCD photodiode array

An important characteristic of noise (NL) is its dependency on integration time - τ (Fig.5). Since read noise is dominant at low light-levels photon noise could be investigated as it increases at longer integration times. On Fig.6 noise levels (NL) of different sensitivities are presented.

$$NL = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(S(n) - S_{mean})^2} \qquad (3)$$

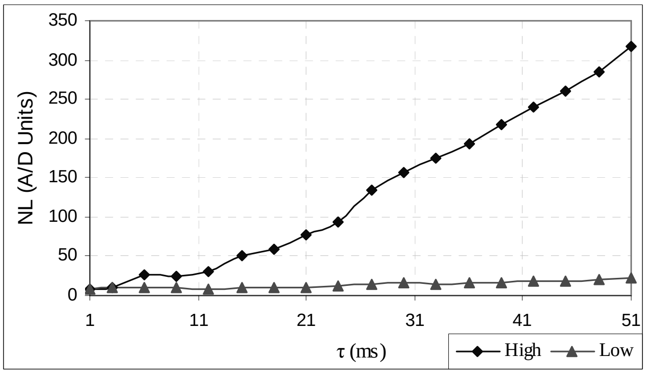

Fig. 6. Noise levels for high and low sensitivity

High sensitivity is achieved with setting different feedback capacitance in the CCD sensor – 0.5pF (high sensitivity) and 10pF (low sensitivity). It is clearly seen that the noise levels increase when larger integration times and a higher sensitivity are applied.

B. Dynamic range

Dynamic range is typically specified as the maximum achievable signal (full well capacity) divided by the CCD sensor noise. It is calculated with formula (4).

$$Dynamic\ Range = 20\lg\left(\frac{S_{sat}(n)}{S_{noise}(n)}\right) \qquad (4)$$

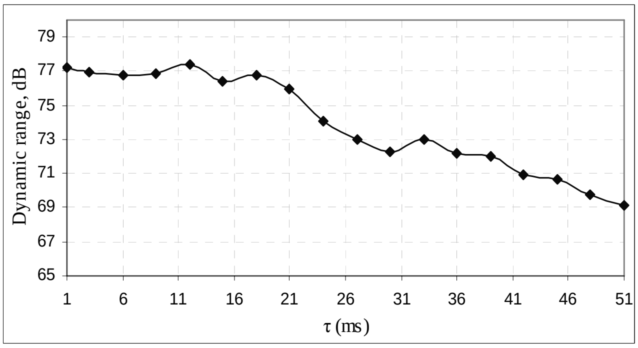

Fig. 7. Dynamic range of the CCD photodiode array

Integration time affects the dynamic range of CCD photodiode array as illustrated on Fig.7. The increase of integration time (τ) produces an increase in dark current and subsequent decrease in dynamic range. At higher sensitivity (lower feedback capacitance) the higher noise levels result also in decrease of dynamic range. The presented graphic on Fig.8 illustrates the characteristics of dynamic range at different sensitivity.

C. Linearity

An important characteristic of fiber-optic interrogation systems is the linearity in response to incident light. Two common techniques are introduced for the measurement and

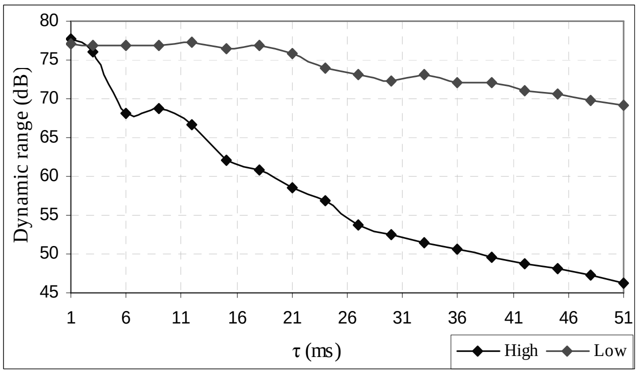

Fig. 8. Dynamic range for two different sensitivities

calculation of the deviation from linearity – measuring output signal as a function of integration time - τ (Fig.9) and measuring output signal as a function of power of incident light - P_i (Fig.10). Nonlinearity is calculated with formula (5).

$$Nonlinearity = \frac{Max.\ Deviation}{Max.\ Signal\ Level} 100,\ \% \qquad (4)$$

The acquired results are shown in Table II. The relatively higher nonlinearity at high sensitivity results from increased noise levels of measured output signals.

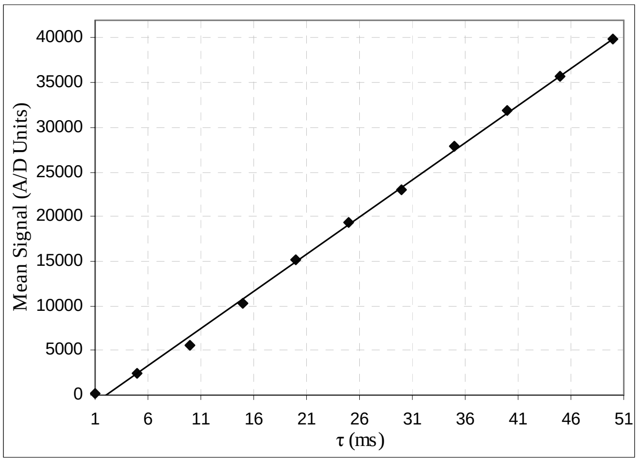

Fig. 9. Linearity as a function of integration time

TABLE II
NONLINEARITY CALCULATION RESULTS

Characteristic	Nonlinearity, %
S(n) = F(Integration time)	
Low sensitivity	1.18
High sensitivity	1.29
S(n) = F(Incident power)	
Low sensitivity	0.83
High sensitivity	1.21

Nonlinear response is usually observed at high illumination intensity. It results in saturation of the pixels and no further change in signal is recorded. Nonlinear response may also result at extremely low illumination levels.

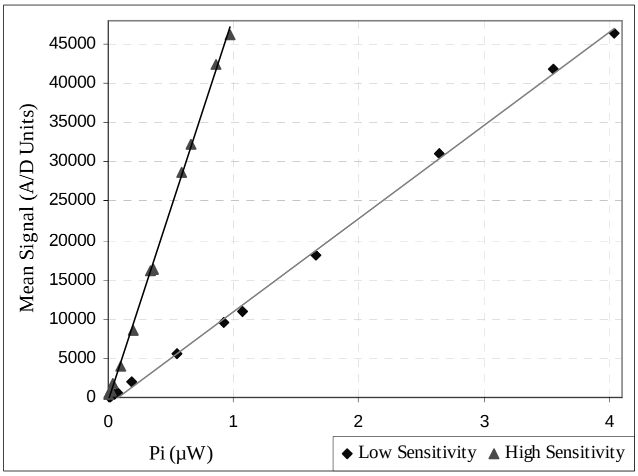

Fig. 10. Linearity as a function of incident power P_i

IV. CONCLUSION

The interrogation system developed and tested here is found to be particularly suitable for spectrally encoded fiber sensors in the 900-1700 nm range [3]. Although the noise levels increase significantly with integration time for the case of high sensitivity, the measured dynamic range even at high sensitivity is better than the typical gratings transmission depth of 30 dB. This is largely due to the far greater increase of the average signal level with integration time. For both high and low sensitivity the sensor array exhibits high linearity in the response.

The investigated CCD linear photodiode array has very good characteristics and is highly appropriate for fiber grating interrogation system. The main advantages of this CCD photodiode array are the increased dynamic range, low noise levels and good linearity of response which are verified with the conducted experimental studies.

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