A 180-nm CMOS Time-of-Flight 3-D Image Sensor

(Invited Paper)

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Abstract—**We report on the design and the experimental characterization of a new 3-D image sensor, based on a new 120-nm CMOS-compatible photo-detector, which features an internal demodulation mechanism effective up to high frequencies. The distance range covered by our proof-of-concept device spans from 1-m to a few meter, and the resolution is about 1-cm.**

I. INTRODUCTION

3-D image sensors can measure the distance of the different points in the scene, yielding a depth map of the observed object in addition to the standard 2-D intensity map. These systems are becoming increasingly attractive in robotics and industrial applications, and some interesting prototypes have been proposed [1-3], covering a wide range of distances (typically from 10 cm to 100 m) and with resolutions spanning from mm for short-range applications, up to 5-10 cm for longer distances. Some 3-D systems are also commercially available [2,4], but their complexity and high cost prevent them so far from being appealing for robotics and industrial applications.

In this paper, we present a compact, and potentially low-cost "3-D camera" for short-range applications (30-400 cm) with a resolution in the order of 0.5-3 cm.

To mitigate laser safety issues, we try to implement the Time-of-Flight rangefinder [1] measurement with a low-power (for example, Class 1-2) pulsed or sine wave modulated laser illuminator [1]. As it is well known, sine wave modulation is the preferred scheme [1] when low power is mandatory, as it allows obtaining a good resolution with reasonably low bandwidth even at short distances. To reduce the burden of electronic circuits to be integrated along with the photodetector and save chip area, we have chosen to employ a new type of CMOS-compatible photodetector, one which combines high frequency performance with an intrinsic capability of signal demodulation.

II. SYSTEM DESIGN

The 3-D system performance can be described by a *power budget* equation, as discussed in Ref. [1], $P_r / P_s = \delta D_r^2/4L^2$, where P_r and P_s are the optical received and transmitted power, respectively, L is the distance to the target and D_r is the diameter of the receiver optics. Coupling this equation with that describing the signal to noise ratio (S/N), the *system equation* $GP_s = (S/N)\, P_n\, 4L_{eq}^2/D_r^2$ is obtained, where G is the receiver gain and P_n is the input equivalent noise power [1], which in turn is given by the sum of the shot-noise (P_{sh}), background noise (P_{bg}) and electronic noise (P_{ph0}) contributions.

In Fig.1 the equivalent transmitted power GP_s is plotted as a function of distance L, highlighting the region of interest for the 3-D system parameters as compared to pulsed, long distance telemeters and to sine-wave modulated rangefinders for topographic applications [1].

In Fig.2, the three basic noise contributions affecting the performance of the telemeter detector and input preamplifier are shown, ain terms of equivalent (optical) power referred to the system input. As can be seen from both Figures, the proposed 3D camera can be favourably compared to more traditional approaches in terms of required power for distances in the range from 1 to 10 m.

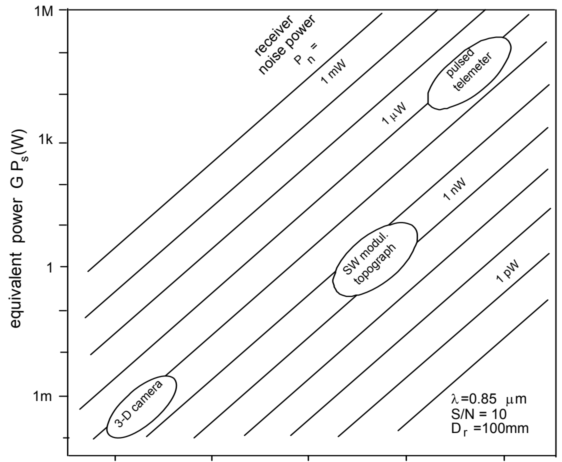

Figure 1. Illumination power required by the 3-D camera as a function of maximum range L, compared to the representative cases of SW (topographic) and pulsed (geodetic) rangefinders.

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In Fig.2, the three abovementioned noise contributions are shown, as referred to the system input. As can be seen from both Figures, the proposed 3-D camera compares favourably to the more traditional approaches in terms of required power for distances in the range from 1 to 10 m.

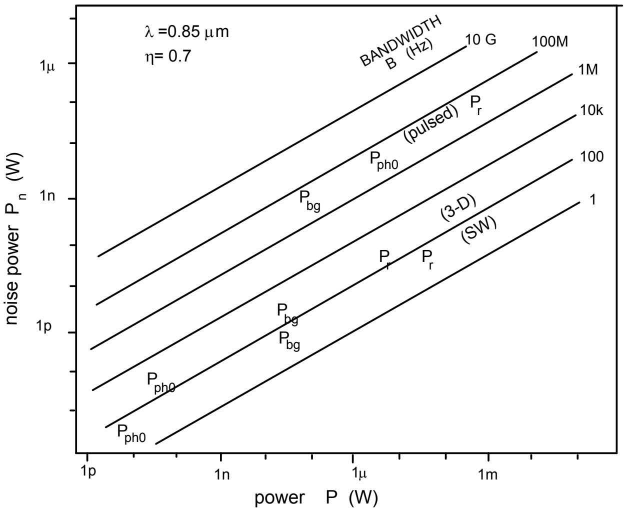

Figure 2. Evaluation of the different noise contributions affecting the signal in a pulsed and in a sine-wave modulated (or 3-D) telemeter

III. THE CAPD PHOTODETECTOR/DEMODULATOR

The Current Assisted Photonic Demodulator (CAPD) is a CMOS compatible electro-optical mixer, which has been recently proposed for use in a Time-of-Flight distance measuring system [5]. A cross section of the device is depicted in Fig.3, where we can also see two modulation electrodes (M1 and M2) and two collection electrodes (D1 and D2).

Light is absorbed in the centre of the device, creating an electron cloud, which can be controlled through the modulation electrodes. The voltage applied between M1 and M2 creates an electric field in the absorption region that guides the photo-generated electrons towards one of the two collection electrodes. Since the path between the modulation electrodes is conductive, a hole current flows between the modulation electrodes. This device offers some remarkable advantages: good demodulation efficiency and sensitivity (also deep in the substrate), good frequency response (see Fig.4), and the possibility of fabricating pixels containing only a few transistors. The main drawback of the device is the power dissipation arising from the modulation current. A high modulation voltage will be necessary to obtain good demodulation efficiency at high frequency, but this will also cause an increase of the modulation current.

A trade-off between speed of operation and power dissipation is therefore necessary, and power consumption will be one of the main issues when dealing with CAPD-based pixel arrays. Numerical device simulations have been used to gain deep insight into the CAPD operation and of the trade-offs governing its performance.

Based on simulation results, CAPD prototypes have been designed and fabricated in a standard180-µnm CMOS process, showing DC characteristics in good agreement with simulation predictions.

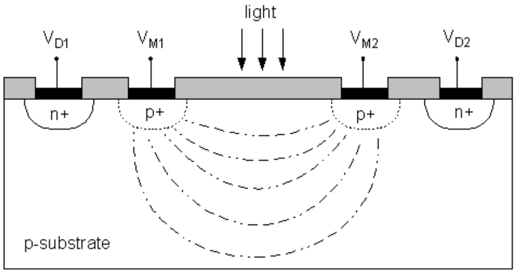

Figure 3. Schematic cross-section of a CAPD photodetector.

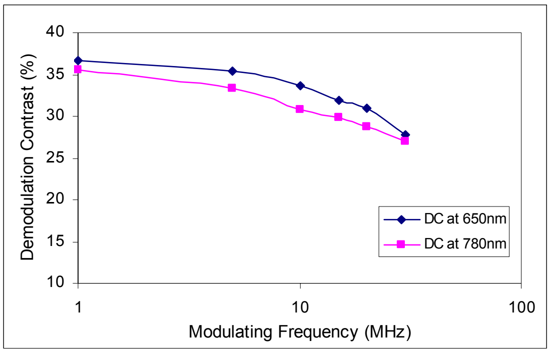

Figure 4. Demodulation contrast as a function of modulation frequency at two wavelengths.

In order to test the demodulation efficiency at high frequency (as reported in Fig.4), devices were characterized using the experimental setup of Fig.5: an arbitrary signal generator, coupled to a differential amplifier, allows for simultaneous control of the two modulation electrodes (out of phase) and a of laser emitter (with arbitrary phase delay Δφ). Using sine wave signals at the same frequency, the current measured at the collection electrodes features a DC component, containing the phase delay information (proportional to cos(Δφ)), and other components at 1x and 2x the modulation signal frequency, that can be easily filtered. For these tests, filtering action has been automatically achieved by using a semiconductor parameter analyzer (HP4145) to measure the average current at the device terminals.

The demodulation contrast, defined as the ratio of the peak-to-peak amplitude and the mean value of the sine wave signal, is shown as a function of the modulation frequency in Fig.4 for two different wavelengths: as can be seen, it remains at high values up to the maximum frequency allowed by the adopted test setup (45 MHz). Results are slightly better at the lower wavelength because charge modulation is less effective deeper in the substrate. Further details on experimental data relevant to CAPD prototypes are given in [6].

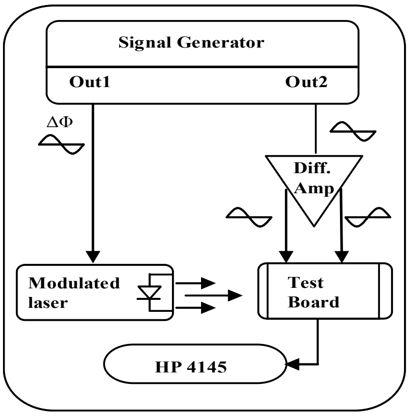

Figure 5. Block scheme of the experimental setup.

IV. CIRCUIT DESIGN AND CHARACTERIZATION

Owing to the intrinsic properties of the photodetector, circuit complexity at the pixel level can be minimized. In fact, demodulation can be accomplished by integrating the photocurrent at the two device terminals, an operation that is possible using a standard architecture with 3 transistors (reset, address, source follower). In this case, the circuit is slightly modified to process two signals in each pixel, and requires a total of 10 transistors.

By doing so, the pixel size can be decreased down to 10-µm while maintaining a reasonably good fill factor (~25%). The pixel outputs are amplified and filtered at column level by CDS (Correlated Double Sampling) circuits, and the output buffer provides further filtering action based on the DDS (Double Differential Sampling) technique. A full image sensor, comprising a 160x120 pixel array, has been fabricated in 0.18-µm CMOS technology and is currently being tested.

As an illustration, a result obtained from a prototype sensor board, coupled to a low power (<50mW), 850-nm LED illuminator modulated at 20 MHz, is reported in Figs.6 and 7: the accuracy of distance measurement in the range from 1 to 4 m (Fig.6) is in the order of a few cm. Moreover, the system is shown to effectively reconstruct 3-D images (Fig. 7).

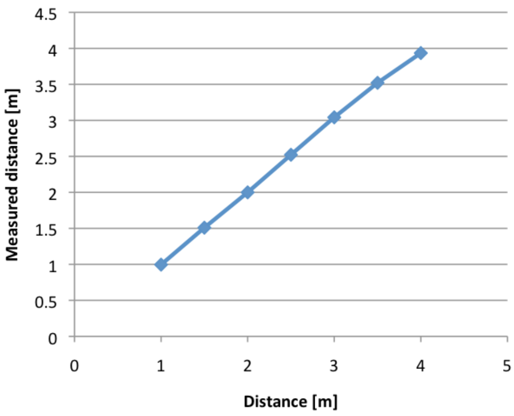

Figure 6. Example of experimantal results of distance measurement.

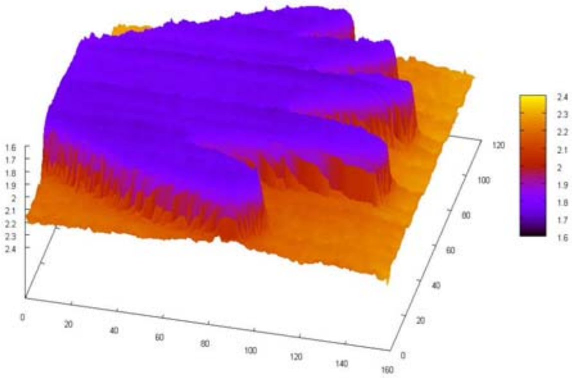

Figure 7. An example of a 3-D image of a hand being picked up by the system.

V. CONCLUSIONS

We have reported on design aspects and first experimental results relevant to a new 3-D CMOS image sensor. Current-assisted photonic demodulators (CAPDs) proved to effectively operate up to high frequencies (>45 MHz) and allowed for simple circuit architecture, resulting in a 10-µm pixel size with 25% fill factor.

The characterization of a full image sensor using the 160x120 pixel array coupled to a LED based illumination module is under way.

ACKNOWLEDGMENT

This work was supported by the Italian Ministry for Education, University and Research (MIUR) under the PRIN 2007 Project n. 2007AP789Y “Time-of-Flight Range Image Sensor (TRIS)”.

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