Demonstration of normalized differential detection using smart pixels with smart illumination
by XiaoFang Chen

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Physics
Montana State University

Abstract:
Smart Pixels with Smart Illumination (SPSI) is a new concept in sensor array technology. It connects the emitters and detectors of an integrated array dynamically, which greatly improves the sensor functionality and opens the door to many exciting potential applications. We use a single pixel that consists of one Vertical Cavity Surface Emitting Laser (VCSEL) and two Metal Semiconductor Metal (MSM) detectors on an opto-electronic (OE) chip to demonstrate normalized differential detection with the SPSI concept. Our experimental data match the theoretical predictions well, which shows that normalized differential detection with the SPSI concept is practical. Two VCSEL/MSM OE chips were characterized and the data are presented in this thesis for documentation and comparison.

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MONTANA STATE UNIVERSITY–BOZEMAN
Bozeman, Montana

May 2000

APPROVAL

of a thesis submitted by

XiaoFang Chen

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date May 19, 2000

ACKNOWLEDGMENTS

I would like to thank a number of people for helping me complete my project and this thesis. I send special thanks to Dr. Kevin Repasky, who designed the optical part for my project, gave me the constant support in research, read my thesis carefully and offered many suggestions on how to improve it. I own him a lot for my progress in this thesis. I am also appreciative to other members in Dr. Babbitt's lab for creating a friendly and intellectual atmosphere. I thank Norman Williams for helping me machine the metal holders for my project. I am thankful to Steve Kelly, who helped me build the printed circuit boards. I also thank Lei Meng for taking the wonderful photographs for my thesis. A warm thanks goes to Margaret Jarrett, who helped me deal with all kinds of paper work so I could focus on my research. I am obliged to Dr. Alain Tchouassi, who spent a lot of time to read my thesis and help me improve it.

I am most grateful to my advisor and mentor, Dr. William Randall Babbitt. Dr. Babbitt introduced me to this exciting topic, gave me the freedom to do this research, and was always there when I needed help. He never blamed me for my mistakes, instead he encouraged me to learn from them and felt happy when I did. His skills as a mentor helped me through every critical part of my project. His attitude towards research and life had a wonderful influence on me that cannot easily be measured.

I am indebted to my family back in China. Even though they are not here with me, I can feel their encouragement everyday. They are the source of my strength.

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Semester of Graduation: Summer 2000
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Title: Demonstration of Normalized Differential Detection Using Smart Pixels with Smart Illumination
Keywords: Smart Pixels with Smart Illumination, normalized differential detection, Vertical Cavity Surface Emitting Laser (VCSEL)/Metal Semiconductor Metal (MSM) detector chip, Opto-Electronic (OE) feedback

CHAPTER 1

INTRODUCTION

Smart pixel[1-6] arrays integrate optical devices and processing electronics on a single semiconductor chip. Current research with smart pixel[7-13] arrays exploits their capability to perform parallel processing of large pixelated images. Though the major focus of smart pixels research has been optical interconnects[14-19], the image sensing applications can also take advantage of the smart pixel technology.

Generally, a scene needs to be illuminated by some kind of light source in order to be sensed by a photodetector sensor array. Conventional sensors rely on illumination that has no connection with the detectors. The simplest source of illumination is ambient light whose random nature such as its unpredictable spatial, temporal, and spectral characteristics leads to sensing problems. An improved source of illumination is built-in illumination with fixed illuminating power. The illuminating power level is set to keep the detectors within their dynamic range when light is reflected from a scene. However, the variations of reflectivity of the scene can affect the sensor performance. A scene with high reflectivity will saturate the detectors, while a scene with low reflectivity will be below the detector's noise floor. Smart pixels with smart illumination (SPSI)[20-22], as described below, is a new concept in image sensor technology. SPSI can alleviate the problem stated above, and can open the door to many potential applications. These applications[20-22] include edge detection, scribe line tracking, spotlight tracking, background subtraction, crosstalk elimination, neural networks, etc.

SPSI connects the emitters and detectors of an integrated array dynamically. Each pixel includes one emitter and one (or more) detector. The emitter is the illumination light source and its illuminating power level can be adjusted dynamically, for instance according to different reflectivities of the scene. Thus, the reflected light from the scene can be sensed by the detectors and always be within the sensor's dynamic range. This goal is reached through electronic feedback from the pixel's detectors to its emitter.

Feedback is used in electronic circuits for stabilizing amplifiers, improving bandwidth, and de-sensitizing the performance of circuit to random variations in device parameters. SPSI couples the electronic feedback to its optical path and greatly improves the sensor functionality. Using SPSI, the image itself can provide information to dynamically control the illumination. A much more efficient sensor can be made if SPSI is utilized successfully.

This thesis uses a single SPSI pixel to demonstrate normalized differential detection with the SPSI concept. The single SPSI pixel explored in this thesis consists of one laser and two detectors on an opto-electronic (OE) integrated chip. The configuration of this single SPSI pixel is depicted in Figure 1. It is one of SPSI's many configurations. The feedback is the sum of the electronic signals generated by the two detectors and can dynamically control the laser output power. The output of this system is the difference of the electronic signals generated by the two detectors and measures the normalized difference of two reflectivites. An SPSI edge detector can detect small variations in reflectivity of images whose reflectivities vary slowly spatially. The demonstration system in this thesis is very useful for the research of SPSI edge detector.

In this thesis, two OE chips were characterized. One laser and two detectors with the best qualities were selected to comprise the single SPSI pixel. The optical part of the pixel was designed and the optics were aligned successfully. The electronic circuits for the pixel were built and performed excellently. The simple model of the single SPSI pixel was modified to describe the experimental system. The experimental results match the prediction of the new model well.

This thesis is organized as follows.

Chapter 2 uses the demonstration system to explain SPSI concept. The optical design for a single SPSI pixel is described. In this thesis, a binary phase grating forms the basis of an optical train used to demonstrate SPSI. The tolerance of the optical system is studied. The block diagram of the OE feedback circuit is described.

Chapter 3 describes the characteristics of the OE chip being used. The power-current (P-I) relationship of the lasers and polarization properties are characterized. The method of determining the spot size of the laser is described. The current-power relationship (I-P) of the detectors is presented.

Chapter 4 describes the optical and electronic setup for the demonstration of SPSI. The alignment procedure is described and accuracy of the alignment is studied. Finally, experimental results are compared with theoretical calculations

A brief discussion of the results is presented in Chapter 5.

CHAPTER 2

THEORY

SPSI pixels can have many configurations. One possibility is illustrated in Figure 1, which represents a single pixel performing normalized differential detection, the building block for an SPSI edge detector. This configuration is explored in this thesis. The light output of the laser, P_{out}, is split by a binary phase grating into two equal-intensity beams. Those two beams illuminate two adjacent spots (1 and 2) on the object. The two spots have reflectivity of $\Re_1$ and $\Re_2$. The beam reflected by spot 1 is split by the grating again. One of the split beam (P_1) is focused onto detector 1 (D_1) and the other split beam is focused back to the laser. Similarly, the beam reflected by spot 2 is split into two beams, one of which (P_2) is focused to detector 2 (D_2) and the other one is focused back to the laser. Although about half of P_{out} is fed back to the laser, no instability of the laser operation is observed in the experiment. Other configurations have been suggested to alleviate this loss in efficiency and feedback into the laser, but require polarization control of the lasers, which is not available yet. The electronic circuit generates some voltage signal V_1 (V_2) proportional to the illuminating power P_1 (P_2) on the detector. The sum (V') of V_1 and V_2 is compared to a pre-set reference voltage V_{ref}. The output voltage of the comparator modulates the output of the current driver and therefore modulates P_{out}. P_{out} is adjusted automatically through the optical and electronic

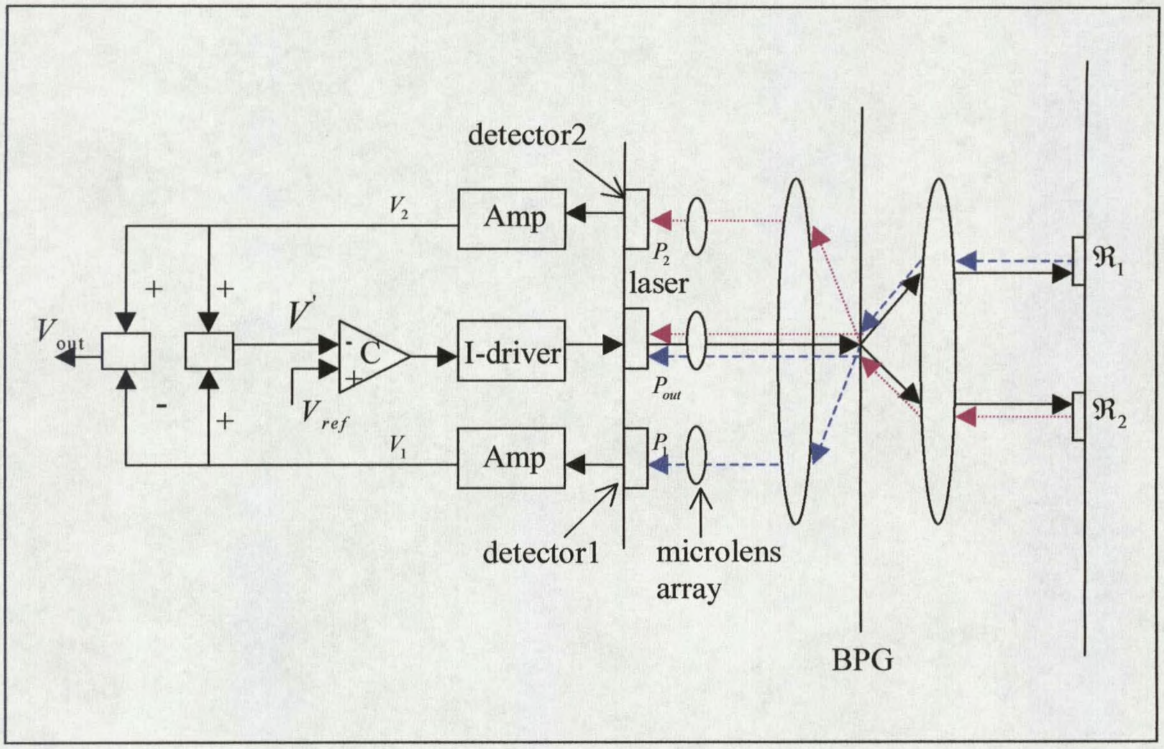

Figure 1. Schematic of the electronics and optics for a single SPSI pixel. C is a comparator, Amp is an amplifier, I-driver is a current driver, BPG is a binary phase grating. $\Re_1$ and $\Re_2$ are reflectivities of the two spots on the object.

feedback. For example, when V' is less than V_{ref}, the feedback function will make P_{out} increase. On the other hand, when V' is more than V_{ref}, the feedback function will make P_{out} decrease. This forces the total laser output that is proportional to V' to be adjusted so that $V' = V_{ref}$. Since $V' = V_1 + V_2$, this means the average optical power on the detectors is held constant. This can be used to keep the detectors in their optical operating range. The output of the pixel, V_{out}, is the difference between V_1 and V_2. V_{out} is