Two-Dimensional Optoelectronic Digital Halftoning Processor

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1 Executive Summary:

A two-dimensional (2-D) multi-channel 8x8 optical interconnect system was developed and investigated in optoelectronic processing architectures as a digital halftoning image processor. The system was designed and fabricated using complementary metal-oxide-semiconductor (CMOS) driven 850-nm vertical-cavity surface-emitting laser (VCSEL) arrays and the p-i-n photodetector (PD) arrays with corresponding wavelengths. The configurations of these 2-D VCSEL and PD arrays are in an 8x8 geometry with a 125-µm device pitch, which yield an interconnect density of 64 interconnects/mm^2. Individual VCSELs have been found to have 3-dB bandwidth as high as 6 Gb/s. The interconnects were integrated by flip-chip hybridization of VCSEL and PD chips onto silicon-on-sapphire (SOS) CMOS for the operational wavelength of 850-nm.

We constructed the entire system under a free-space configured 2-D optical interconnects driven by silicon-on-sapphire (SOS) circuits and carried out characterization of the system on data transmission using pseudo-random bit stream (PRBS) data sequence. Eye diagrams from single channels were obtained and analyzed using a pattern generator and a digital oscilloscope at data rates from 155 Mb/s to 1.5 Gb/s. BERs of 10^{-12} to 10^{-2} were measured within such bandwidths. Using a statistical model of Gaussian distribution for the random noise in the transmission, we used a method to compute the BER instantaneously in synchronous with the digital eye-diagrams. Direct measurements on this interconnects were also taken on a standard BER tester for verification. We found that the results of the two methods were in the same order and within 50% accuracy. The integrated interconnects are being investigated in optoelectronic processing architectures such as digital halftoning image processor. Error diffusion networks implemented by the inherently parallel nature of photonics promise to provide high quality digital halftoned images. Error diffusion networks implemented by the inherently parallel nature of photonics promise to provide high quality digital halftoned images.

2 Introduction

Optics has long held the promise of high-speed, high-throughput parallel information processing. The focus of its early applications was on analog signal processing techniques such as the optical

Fourier transform, matrix-vector processors, and correlators. During this period, optics was used almost exclusively for front-end, pre-processing of wide-bandwidth, high-speed analog signals, which were subsequently digitally processed using electronic techniques. Digital signal processing, however, provides higher resolution, improved flexibility and functionality, and increased noise immunity over its analog counterparts and therefore is the preferred method for accurate signal processing. Since the majority of signals encountered in nature are continuous in both time and amplitude, the analog-to-digital (A/D) interface is generally considered to be the most critical part of the overall signal acquisition and processing system. Because of the difficulty in achieving high-resolution and high-speed A/D converters, this A/D interface has been and continues to be a barrier to the realization of high-speed, high-throughput systems.

3 Digital Halftoning Background

Digital image halftoning is an important class of A/D conversion within the context of image processing. Halftoning can be thought of as an image compression technique whereby a continuous-tone, gray-scale image is printed or displayed using only *binary-valued* pixels. This particular technique has important applications to Army users in such areas as transmission of high-resolution maps and images to battlefield locations using tactical communication links and facsimile. Error diffusion is one method of achieving digital halftoning in which the error associated with a nonlinear quantization process is diffused within a local region and subsequent filtering methods employed in an effort to improve some performance metric such as signal-to-noise ratio. Classical error diffusion is a one-dimensional, serial technique in that the algorithm raster scans the image from upper-left to lower-right and as a result, introduces visual artifacts directly attributable to the halftoning algorithm itself. A fully parallel implementation of the error diffusion algorithm, however, provides the advantage that all pixel quantization decisions are computed in parallel and therefore the error diffusion process becomes two-dimensional and symmetric. Visual artifacts attributable to the halftoning algorithm are eliminated and overall halftoned image quality is significantly improved. An optoelectronic implementation of the error diffusion algorithm is one approach to this fully parallel implementation. In addition, the inherent parallelism associated an optical implementation reduces the computational requirements while decreasing the total convergence time of the halftoning process.

4 Error Diffusion Network Halftoning

Previously[1], we developed a new artificial neural network architecture based on the mathematical foundation of the error diffusion algorithm, which we call an *error diffusion neural network*. One significant advantage of this new implementation is that arbitrary size and shape diffusion kernels can be implemented thereby reducing the visual artifacts which have become characteristic of halftoned images. This can be accomplished with no penalty in terms of computation speed. The error diffusion neural network has been implemented in software and computes the halftoned image asymptotically faster than a conventional Hopfield-type neural network and also provides full-rank connectivity across the entire image. We have quantitatively compared the resulting halftoned images with those produced using other halftoning techniques using performance metrics such as the radially averaged frequency spectrum and anisotropy of

continuous-tone gray-scale images[2]. The halftoned images that result from this new halftoning process are currently the *best* halftoned images available, producing artifact-free images.

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We have been developing a hardware implementation of the error diffusion network to parallel the software simulation. The complete optical interconnect system consists of the computer, VCSEL array, diffractive optical element, and detector array. The function of the detector array is being temporarily performed by a charge-coupled detector (CCD).

5.1 Halftoning Processor Components

We have been investigating an optical interconnect technique using a diffractive optical filter to compute the fanout values. In an independent portion of this project[3], an iterative algorithm was used to design a 7×7 error diffusion kernel using a 128×128, eight-level, phase-only diffractive optical element. The design, fabrication, and experimental characterization of this diffractive optical filter successfully constituted a proof-of-concept demonstration of the ability to accurately weight and distribute the error signal using optical techniques. Other diffractive optical filter designs have also included a continuous-phase-profile element, which provides the ability to evaluate the impact of alternate fabrication methods on the fidelity of the devices. This diffractive optical filter will fan-out the optical signal generated by a 850 nm vertical cavity surface-emitting laser (VCSEL). These VCSELs were designed, grown, and processed at the Army Research Laboratory in Adelphi, Maryland. The array is arranged in an 8 x 8 array at a 125 μm pitch in a square pattern. A similar detector array has been provided by ARL so that the interconnected signal can be received. The VCSEL and detector arrays are controlled by a computer with individual control of 64 analog output channels and 64 analog input channels.

5.2 Digital Halftoning Processor Operation

A initial gray-scale image to be processed by the digital halftoning system is loaded into the computer. The error by individual pixel is computed with a threshold function and transmitted using the analog channels to the VCSEL array. The VCSELs lase according to the input pattern from the controlling computer. The light output from the VCSEL array is incident upon the diffractive optical element which fans the individual channels out in the 7x7 pattern onto the detector array. The intensities from the various DOE outputs combine through the superposition principle and form the diffused error output. This error output is then read into the computer and forms the new image. This process is iterated until the image is deemed of appropriate quality. The 8x8 hardware limitations of the current system force a typical image to be partitioned into many sections and passed through individually until complete. Significant border effects are introduced by the 7x7 fanout pattern and the 8x8 VCSEL and detector arrays. The two conditions limit the lossless halftoning process to the inner 2x2 VCSELs. The use of any other VCSELs will cause the fanout pattern to fall outside the detector array.

6 Bit Error Rate Computation Method

The bit error rate is a critical parameter in the performance of a processing system. This parameter is typically characterized through the use of high-end and scarce test equipment (Bitlyzer). While this equipment was initially available for our use, it was unavailable for later testing. We developed an equivalent bit error rate capability using less expensive and much more readily available laboratory equipment. The technique has the added advantage of instantaneously computing the bit error rate instead of waiting for the entire test to complete on the other test setup. The remainder of this section is from Liu, Gollsneider, et al[4].

By definition, the BER is the probability that a 0 bit signal is misrepresented as a 1 bit or vice versa. This can be mathematically described as:

$$BER = P_T(0)P_{R(1|0)} + P_T(1)P_{R(0|1)} = \tfrac{1}{2}(P_{R(1|0)} + P_{R(0|1)}), \qquad (1)$$

where $P_{R(x|y)}$ is the probability that, if a bit y is transmitted, a bit x is received. It is assumed that, since the PRBS is randomly determined, that the probability for transmitting a 0, $P_T(0)$, or 1, $P_T(1)$, is equal, i.e. $P_T(0) = P_T(1) = ½$. Thus the coefficient ½ represents the probability that the initial conditions are satisfied.

If it is possible to find a model for the probability density function of the signal at the two voltage levels, it will be possible to derive the BER of the transmission with which the signal is associated from the statistics of the model, using the above formula. Since there are many sources of random noise, the distribution of the signal approaches a Gaussian (normal) distribution. Therefore, it is reasonable to use Gaussian models to analyze the BER. By applying Gaussian distributions for the probability density functions of the voltages, the BER can then be computed by the following formula:

$$BER = \frac{1}{2}\left(\int_{V/2}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma_0} e^{-t^2/2\sigma_0^2}\,dt + \int_{-\infty}^{V/2} \frac{1}{\sqrt{2\pi}\,\sigma_1} e^{-(t-V)^2/2\sigma_1^2}\,dt\right), \qquad (2)$$

where σ_0 and σ_1 are standard deviations of voltages 0 and V which represent 0 and 1 bit signals. The first integral represents $P(0|1)$, and the second integral represents $P(1|0)$. Graphically, each integral also represents the area of the tail of the probability distribution past the decision threshold. Evaluation of this formula leads to:

$$BER = \frac{1}{4}\left(erf\left(\frac{V}{2\sqrt{2}\,\sigma_0}\right) + erf\left(\frac{V}{2\sqrt{2}\,\sigma_1}\right)\right). \qquad (3)$$

Here we can see that BER can be calculated using the error function *erf*(*x*). Figure 11 illustrates two overlapped Gaussian distributions, representing transmitted 0 and 1 bit data signals, applied for the BER computation.

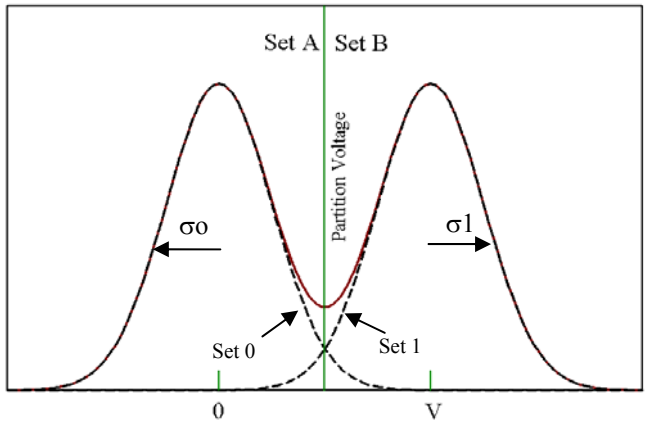

Figure 1. A simple representation of transmitted data signals by two equivalent Gaussian distributions with standard voltage deviations σ_o and σ_1.

Placing the decision threshold voltage at the midpoint of the two sets during the computation does not guarantee an optimum BER, especially when the two standard deviations are unequal. Instead, the optimum BER occurs when the tails of the curves are equal. It can be shown that the optimum BER is given by:

$$BER = \frac{1}{2} erf \left(\frac{V}{\sqrt{2}(\sigma_0 + \sigma_1)} \right) . \qquad (4)$$

It should be noted that Equations 3 and 4 are equivalent when $\square_0$ and $\square_1$ are equal. It is also significant that the quantities $V/\square_0$ and $V/\square_1$ are related to the signal-to-noise ratio (S/N) of the communications link, because the variance $\square^2$ is related to the mean squared of the noise at a voltage level. This draws a direct correlation between the S/N and the BER.

Since the BER is determinable from knowledge of the statistical distribution of the two sets of voltage levels, the problem now lies in distinguishing the two sets apart experimentally. When it is possible to distinguish the two sets by prior knowledge of the transmitted PRBS, the problem is solved. This is the approach that the bit error rate tester uses to separate the voltage levels. However, such knowledge is not available in a real transmission. With knowledge of the voltages acquired from the optical receiver, it is impossible to discern with total certainty each set. Therefore, some approximation was employed to distinguish the two voltage sets for computing the BER during our experiments.

We developed a LabView computer program and interfaced it with the oscilloscope that acquires the eye diagram of the operation. BER was computed almost instantaneously as an eye diagram is displayed on the oscilloscope. Figure 12 shows BER data measured from a single interconnect channel by a Bitlyzer (top curve) and by computation from the eye diagrams (lower curve). The measurements covered data rates from 155 Mb/s to 1.5 Gb/s. It can be seen that the results of two methods were in the same order and within 50% accuracy. Compared to the Bitlyzer measurement which involves costly equipment, the computation method that we developed

provides BER in timely fashion and with reasonable accuracy. This method is also very easily implemented to many experimental systems.

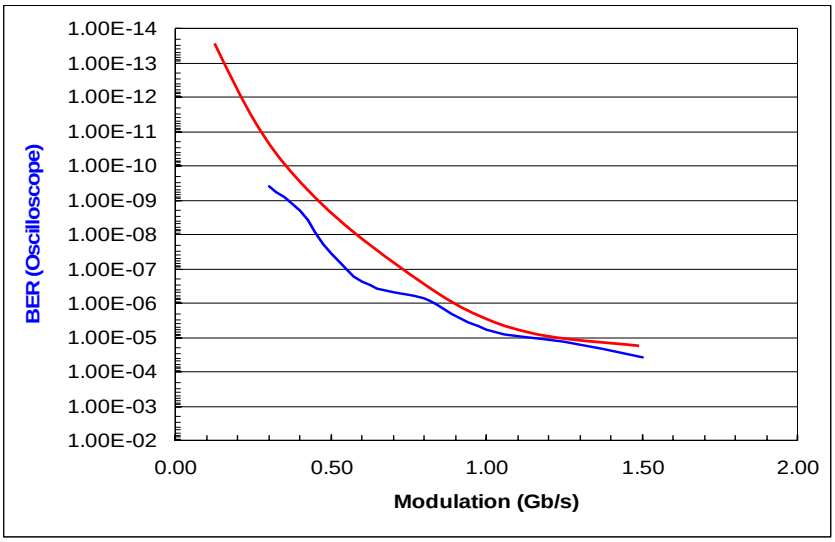

Figure 2. Measured BER data by a Bitlyzer (top curve) and by computation from the eye diagrams (lower curve).

Future Work

The CCD used as an interim step in the opto-electronic digital halftoning system needs to be replaced with the detector array. The performance of the complete opto-electronic processing system needs to be analyzed. The border effects created by the 7x7 fanout pattern and the 8x8 VCSEL and detector arrays needs to be analyzed.

Conclusions

Optics continues to hold the promise of high-speed, high-throughput parallel information processing. The two-dimensional optoelectronic digital halftoning processor promises to deliver fast and parallel data rates with very low power consumption. The instantaneous BER computation method is very useful for many communications fields. Error diffusion networks implemented by the inherently parallel nature of photonics promise to provide high quality digital halftoned images.

References

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