

An Optical Processor for Data Error Detection and Correction Using a (9,5) Binary Code Generator and the Syndrome Decoding Process

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Abstract: Based on a-SiC:H technology, we present an optical processor for data error detection and correction using a suitable (9,5) Hamming binary code generator and the syndrome decoding process. The optical processor consists of an a-SiC:H double p-i-n photodetector with two ultraviolet light biased gates. The relationship between the optical inputs (transmitted data) and the corresponding output levels (the received data) is established and decoded. Results show that under irradiation the device acts as an active filter. Under front irradiation the magnitude of the short wavelength is quenched and in the long wavelength range is enlarged, while the opposite happens under back lighting. Parity bits are generated and stored simultaneously with the data word. Parity logic operations are performed and checked for errors together. An all-optical processor for error detection and correction is presented to provide an experimental demonstration of this fault tolerant reversible system. Two original coloured string messages, having 4- and 5- bits, respectively, are analyzed and the transmitted 7- or 9- bit string, the parity matrix, the encoding and decoding processes, are explained. The design of SiC syndrome generators for error correction is tested.

Keywords: a-SiC:H technology, Error detection and correction, Syndrome decoding process, Hamming binary code.

1. Introduction

In digital transmission systems, an error occurs when a bit gets altered between transmission and reception; that is, a binary 1 is transmitted and a binary 0 is received, or a binary 0 is transmitted and a binary 1 is received. Noise and physical defects in the communication system can cause random bit errors during data transmission. Errors detection codes are generated as a function of the bits being transmitted.

Such codes are appended to the data bits and transmitted together. The receiver evaluates the code based on the incoming bits and compares it with the incoming code to check for errors [1]. Optical/optoelectronic computing is an important topic and several architectures, logical and arithmetic operations were proposed in the literature [2-3]. Remote control applications demand error correction also to be implemented, so that the receiver itself is able to manage error correction [4]. Error coding is a

method of detecting and correcting these errors which ensures information to be transferred intact from its source to its destination. Error coding uses mathematical formulas to encode data bits at the source into longer bit words for transmission. The code word can then be decoded at the destination to retrieve the information. The extra bits, in the code word, provide *redundancy* that, according to the coding scheme used, will allow the destination to use the decoding process to determine if the communication system has introduced errors and, in some cases, correct them avoiding the need of data retransmission.

By using different optoelectronic devices [5-6], strength has been set into the development of all-optical logical functions [7]. Tandem monolithic Si/C structures based on amorphous silicon technology can be reconfigurable to perform optoelectronic logic functions [8-9] due to their nonlinear magnitude-dependent response to each incident light wave, in the visible range. Based on such properties, in this paper we built an optical processor for error detection and correction based on SiC amorphous technology. The design of SiC syndrome generator is presented. The syndrome decoding is analyzed and uses the syndrome bits introduced. A syndrome decoding for a linear code is explained and tested showing the ability to decode a seven and nine linear code efficiently.

2. Experimental Details

2.1. Receiver Design and Operation

In Fig. 1, it is shown the configuration and operation of the optical receiver. The active device is a double pi^2n/pin a-SiC:H photodetector produced by Plasma Enhanced Chemical Vapor Deposition (PECVD). It consists of a $p-i'(a-SiC:H)-n/p-i(a-Si:H)-n$ heterostructure with high resistivity 20 nm thick doped layers ($>10^{17}\Omega \times cm$) packed between two transparent oxide layers (TCO) made of ITO. The deposition conditions and optoelectronic characterization of the single layers and device as well as their optimization were described elsewhere [10-11]. The device acts as an active filter, confining the short wavelength optical carriers in the front photodiode while the long ones are absorbed into the back photodiode (see arrow magnitudes). The medium wavelength ranges are absorbed differently across both [12].

In Fig. 1, a four channel transmission is exemplified. Here, the data is transmitted using four monochromatic (red, green, blue and violet; $\lambda_{R,G,B,V}$) pulsed communication channels (input channels; data code) that are mixed together, each one with a specific bit sequence and are absorbed in different regions depending on their wavelengths. The combined optical signal (multiplexed signal) is received and analysed by reading out the generated photocurrent under negative applied voltage (-8 V), and 390 nm

background lighting, applied either from the front or the back sides of the device. In a four channel data transmission, the square wave of four modulated low power lights of red (R: 626 nm), green (G: 524 nm), blue (B: 470 nm) and violet (V: 400 nm) LEDs were used. In the five channel transmission an extra near infrared (I: 700 nm) LED was added.

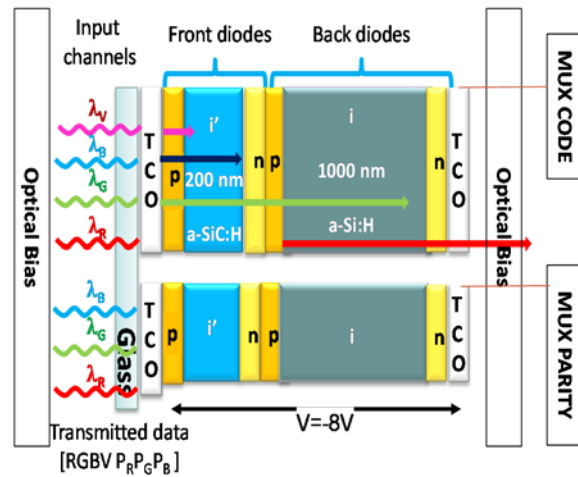


Fig. 1. Receiver configuration and operation.

Hamming codes are code words formed by adding redundant check bits, or parity bits, to a data word [1]. Those code words are verified at the receiver end to check and correct. So, when the transmission uses n input channels ($n=4$ or $n=5$), $n-1$ parity channels are needed to define the parity bits. Here, for parity check, three or four red, green, blue and violet synchronous channels, respectively, were read in simultaneous with the data code. As an application, data was sent through one detector while error detection and correction bits were sent through the other.

2.2. Nonlinear Optical Gain

Five monochromatic input channels in the VIS/NIR range (400 nm-850 nm) illuminated the device separately (transmitted data) or combined (MUX signal) at 12000 bps. The generated photocurrent was measured under negative applied voltage (-8 V) and under front and back steady state irradiation. For each channel, the gain ($\alpha_{R,G,B,V}^V$), defined as the ratio between the photocurrent with and without applied background, was determined.

In Table 1 the optical gains of the input channels used in the transmission are displayed under $2800 \mu Wcm^{-2}$ front (α_F) and back (α_B) irradiation.

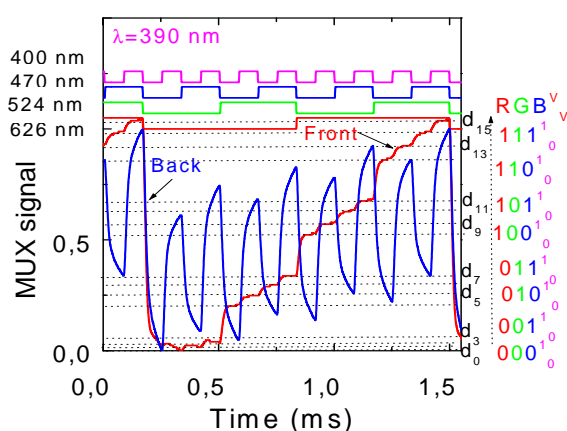
Data measured confirm that the optical gain, under irradiation, depends on the irradiated side and on the incoming wavelength acting as an active filter for the input channels.

Table 1. Front (α_F) and back (α_B) optical gains.

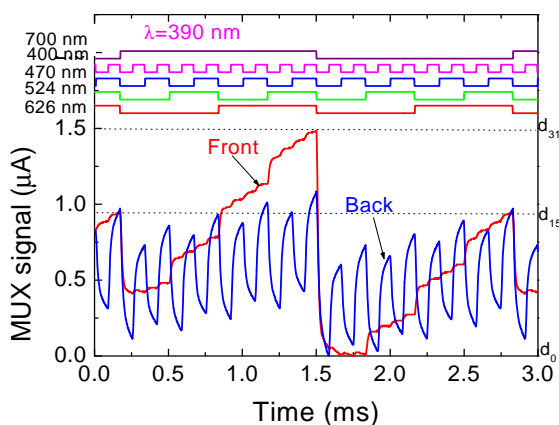
λ (nm)	α_F	α_B
400	0.90	11.60
470	1.07	1.96
524	3.55	0.57
626	4.70	0.45
700	5.55	0.40

3. MUX/DEMUX Receiver

In Fig. 2, the received data, i.e. the MUX code signal, due to the combination of four (Fig. 2(a); 400 nm, 470 nm, 524 nm, 626 nm) or five (Fig. 2(b); 400 nm, 470 nm, 524 nm, 626 nm, 700 nm) input channels are displayed under both front and back irradiations.



(a)



(b)

Fig. 2. MUX signals under 390 nm front and back irradiation. On the top the transmitted channels are displayed: a) Four channels transmission; b) Five channels transmission.

At the top, the input channels (transmitted data) are shown to guide the eyes. In Fig. 2(a), the selection index for the 16-element look-up (d_0 - d_{15} , dotted levels) is a 4-bit binary code (RGBV), while in Fig.

2(b), the selection index for the 32-element look-up (d_0 - d_{31} , dotted levels) is a 5-bit (RGBVI) binary code.

The algorithms to encode and decode are relatively simple and the knowledge of the background acting as selector that chooses one or more of the 2^n sublevels, with n the number of transmitted channels, and their n -bit binary code makes the communication reliable [13]. Results show that to each of the 2^n possible *on/off* states corresponds a well-defined level. In Fig. 2, all the *on/off* states are possible so, 2^n ordered levels are detected and correspond to all the possible combinations of the *on/off* states [14]. Here, under either front or back irradiation, each of those n channels, by turn, are enhanced or quenched differently (see Table 1) resulting in an increase magnitude of infrared/red/green under front irradiation or of the blue/violet, under back lighting. So, by assigning each output level to an n digit binary code weighted by the optical gain of the each channel, the signal can be decoded. A maximum transmission rate capability of 60 kbps was achieved in a five channel transmission.

4. Error Control Based on a-SiC:H Technology

The proximity of the magnitude of consecutive levels (Fig. 2) and noise during the read out process causes occasional errors in the decoded information that should be corrected. To minimise the errors, a parity bit [1] was generated and stored along with the data word. The parity of the word is checked after reading the word. The word is accepted if the parity of the bits read out is correct. If the parity of the bits is incorrect, an error is detected, but it cannot be corrected. An error-correcting code uses multiple parity check bits that are stored with the data word. Each check bit is a parity bit for a group of bits in the data word. When the word is read, the parity of each group, including the check bit, is evaluated. If the parity is correct for all groups, it indicates that no detectable error has occurred. If one or more of the newly generated parity values is incorrect, a unique pattern called a syndrome results that may be able to identify which bit is in error. If the specific bit in error is identified, then the error can be corrected by complementing the erroneous bit.

The standard Hamming code [1] is designed to have a minimum Hamming distance of 3 between any two code words. i.e., the Hamming (7,4) is a standard type of Hamming code that encodes 4 bits (four input channels) of data into 7 bits by adding 3 parity bits (three parity input channels). Taking into account Fig. 2(a), the encoder takes four input data bits [R G B V] to which corresponds one of the possible 16 sublevels and generates three additional parity bits to which corresponds one of the eight (2^3) possible well defined levels:

$$P_R-(VRB) = V \oplus R \oplus B \quad (1)$$

$$P_G-(VRG) = V \oplus R \oplus G \quad (2)$$

$$P_B-(VGB) = V \oplus G \oplus B \quad (3)$$

In a similar way, from Fig. 2(b), the encoder for code takes five input data bits [R G B V I] to which corresponds one of the possible 32 sublevels, and also provides violet redundancy creating the same three additional parity bits, given by the Equations (1), (2) and (3) and an extra fourth parity bit given by Equation (4).

$$P_V-(I) = I \quad (4)$$

The extra bit for the extended code is added as one more parity check bit. This fourth parity equation was chosen to take advantage of the background illumination. Since under front irradiation the 626 nm and 700 nm have similar optical gains in order to decode the near-infrared channel the parity bit matches with the violet bit where the back optical gain is high (Table 1). So, in a four channel transmission (Equations (1), (2), (3)) the parity bits are SUM bits of the three-bit additions of violet pulsed signal with two additional bits of RGB [15]. In a five channel transmission (Equations (1), (2), (3) and (4)), one-bit extra, named I, was added leading to a 16-level $P_R P_G P_B P_V$ MUX for the parities.

To build a code with 5-bit data words [R G B V I] that will correct single-bit errors, we must add the 4 check bits [P_R, P_G, P_B, P_V] generated by Equations (1), (2), (3) and (4) creating extended code words of length 9. In Table 2, all the 32 code word combinations are displayed. For a 4-bit transmission the process was similar and made using the standard Hamming code [14].

Fig. 3, show the MUX signal (solid lines) that arises from to the transmission of the four (Fig. 3(a)) or five (Fig. 3(b)) wavelength channels. The dotted line marks the generation of the synchronized parity MUX transmitted in simultaneous with the data code. Due to the different front and back optical gains (Table 1) the colors red, green, blue and violet were assigned respectively to P_R, P_G, P_B and P_V . The eight, or the sixteen, ordered levels of the parity bits are marked as horizontal dash lines in Fig. 3(a) and Fig. 3(b), respectively. In the right side of figures the eight or the sixteen sublevels and their 3- or 4-bit binary codes are inserted, respectively. On the top the seven or the nine bit word [R, G, B, V (I), $P_R, P_G, P_B (P_V)$] of the transmitted inputs guides the eyes.

Taking into account Fig. 3(a) and Fig. 3(b) the 7- or the 9-bit word at the output of the encoder will be in a bitwise format, with the data and the parity bits separated. It is interesting to notice that different code words can present the same parity bits. For instance, in Fig. 3(a) the levels d_2 and d_{12} present the same parity level p_5 while in Fig. 3(b) the same occur between d_{18} and d_{28} that both present parity level p_{11} .

Table 2. Strings of all possible code words for a (9,5) block code. The message and parity digits [R G B V I : $P_R P_G P_B P_V$] and the received message levels, d_{0-31} , and their correspondent parity levels, p_{0-15} .

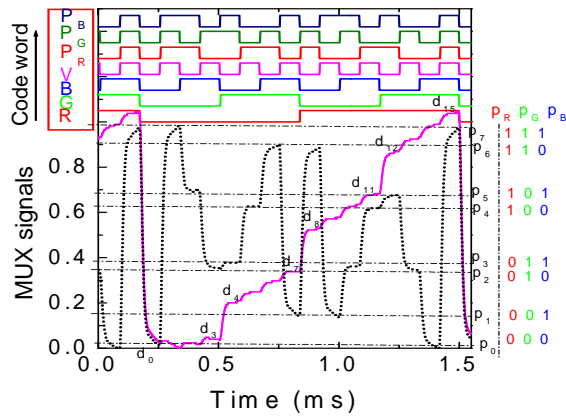
d_{0-31}	R	G	B	V	I	P_R	P_G	P_B	P_V	p_{0-15}
d_0	0	0	0	0	0	0	0	0	0	p_0
d_1	0	0	0	1	0	1	1	1	0	p_{14}
d_2	0	0	1	0	0	1	0	1	0	p_{10}
d_3	0	0	1	1	0	0	1	0	0	p_4
d_4	0	1	0	0	0	0	1	1	0	p_6
d_5	0	1	0	1	0	1	0	0	0	p_8
d_6	0	1	1	0	0	1	1	0	0	p_{12}
d_7	0	1	1	1	0	0	0	1	0	p_2
d_8	1	0	0	0	0	1	1	0	0	p_{12}
d_9	1	0	0	1	0	0	0	1	0	p_2
d_{10}	1	0	1	0	0	0	1	1	0	p_6
d_{11}	1	0	1	1	0	1	0	0	0	p_8
d_{12}	1	1	0	0	0	1	0	1	0	p_{10}
d_{13}	1	1	0	1	0	0	1	0	0	p_4
d_{14}	1	1	1	0	0	0	0	0	0	p_0
d_{15}	1	1	1	1	0	1	1	1	0	p_{14}
d_{16}	0	0	0	0	1	0	0	0	1	p_1
d_{17}	0	0	0	1	1	1	1	1	1	p_{15}
d_{18}	0	0	1	0	1	1	0	1	1	p_{11}
d_{19}	0	0	1	1	1	0	1	0	1	p_5
d_{20}	0	1	0	0	1	0	1	1	1	p_7
d_{21}	0	1	0	1	1	1	0	0	1	p_9
d_{22}	0	1	1	0	1	1	1	0	1	p_{13}
d_{23}	0	1	1	1	1	0	0	1	1	p_3
d_{24}	1	0	0	0	1	1	1	0	1	p_{13}
d_{25}	1	0	0	1	1	0	0	1	1	p_3
d_{26}	1	0	1	0	1	0	1	1	1	p_7
d_{27}	1	0	1	1	1	1	0	0	1	p_9
d_{28}	1	1	0	0	1	1	0	1	1	p_{11}
d_{29}	1	1	0	1	1	0	1	0	1	p_5
d_{30}	1	1	1	0	1	0	0	0	1	p_1
d_{31}	1	1	1	1	0	1	1	1	1	p_{15}

As an example, in Fig. 3(a) the codeword that corresponds to receive the $d_3 = "0011"$ and $p_2 = "010"$ levels are in the same time slot. Since d_3 is too near d_2 the message ($d_2:p_2$) could be measured instead, which is impossible since the d_2 correspondent parity level, $p_5 = "101"$, is too far way. A similar example could be easily obtained from Fig. 3(b). Here, the codeword [10111001] was sent and received as ($d_{26}; p_9$) which corresponds to [101011001], which is impossible since the last four bit should be $p_9 = "1001"$ ($d_{27}; p_9$). So, an error was detected in the transmission and has to be corrected.

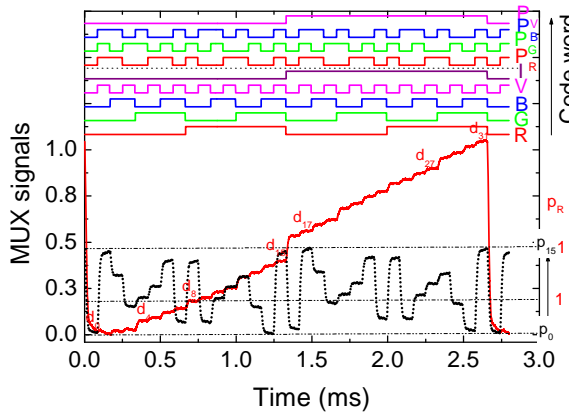
5. Design of SiC Syndrome Generators and Syndrome Decoding

5.1. Syndrome Calculation for a Hamming (9,5) Block Code

The transformation from message bits to code words is linear, so, one can represent each message-to-codeword transformation succinctly using matrix notation.



(a)



(b)

Fig. 3. Code and parity MUX signals under 390 nm front irradiation. On the top the transmitted channels [R G B V P_R P_G P_B] are shown. a) Four channel transmission; b) five channel transmission.

The parity check bits of a (7, 4) block code are generated by Equations (1), (2), (3) and for a (9,5) block code by Equations (1), (2), (3), (4) (see Table 2). To obtain the generator matrix and the parity check matrix, the check bits are related in a five channel transmission as [3]:

$$\begin{bmatrix} P_R-(VRB) & P_G-(VRG) & P_B-(VGB) & P_V-(I) \end{bmatrix}_{\times 4} = \begin{bmatrix} RGBVI \end{bmatrix}_{\times 5} \begin{bmatrix} P \end{bmatrix}_{\times 4}, \quad (5)$$

where P is the parity matrix.

Comparing the above equations with the check bit equations (Equations (1), (2), (3), (4)) we find that P matrix, for a five channel transmission, is given as:

$$P = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

The Generator matrix, G , is taken so that $G_{k \times n} = [I_k : P_{k \times (n-k)}]$, where I_k is the identity matrix which determine the code words and P , the parity matrix, that provides redundancy, and G is given by:

$$G_{5 \times 9} = [I_5 : P_{5 \times 4}] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & : & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & : & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & : & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & : & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & : & 0 & 0 & 0 & 1 \end{bmatrix}_{9 \times 5} \quad (7)$$

The parity check matrix, H is given by:

$$H = [P^T : I_{(n-k)}] = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & : & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & : & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & : & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & : & 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

And the syndrome is given by:

$$S_i = \begin{bmatrix} r & g & b & v & i & P_R & P_G & P_B & P_V \end{bmatrix} H^T \quad (9)$$

So, the output of the syndrome for general received word is a four-bit $S_i = [S_1 S_2 S_3 S_4]$, modulus 2, with:

$$\begin{aligned} S_1 &= (r + b + v + p_R), \\ S_2 &= (r + g + v + p_G), \\ S_3 &= (g + b + v + p_B), \\ S_4 &= (i + p_V), \end{aligned} \quad (10)$$

where each $[S_1 S_1 S_3 S_4]$ is the syndrome bit, and it helps the receiver to diagnose the errors in the received data. In a similar way, in a four channel transmission, the syndrome calculation for a (7,4) block code will give S_4 always zero once the parity check matrix will be given by:

$$H = \begin{bmatrix} 1 & 0 & 1 & 1 & : & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & : & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & : & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

5.2. Syndrome Decoding

For a received word, syndrome decoding pre-computes the syndrome corresponding to each error. If it is 0, then there are no single-bit errors, and the receiver returns the first bits of the received word as the decoded message. If not, then it compares that bit value with each of the stored syndromes. If the syndrome matches, then it means that a data bit in the received word was in error, and the decoder flips that bit and returns the first bit of the received word as the most likely message that was encoded and transmitted. Taking into account H^T matrix, a table (Table 3) is created with the corrective action for each combination of the syndrome bits. These bits are

possible candidates for having an error since any of them could have caused the observed parity errors. A similar table could be generated for four channels transmission with $S_4=0$ [14].

Table 3. Corrective actions for each combination of syndrome bits in a five channel transmission.

S ₁	S ₂	S ₃	S ₄	Corrective actions
0	0	0	0	no errors
1	1	0	0	r have an error, flip to correct
0	1	1	0	g have an error, flip to correct
1	0	1	0	b has an error, flip to correct
1	1	1	0	v has an error, flip to correct
0	0	0	1	i has an error, flip to correct
1	0	0	0	pr has an error, flip to correct
0	1	0	0	pg has an error, flip to correct
0	0	1	0	pb has an error, flip to correct
0	0	0	1	pv has an error, flip to correct

Taking as an example Fig. 3(b), the d_{15} and d_{14} levels are too close. The message ($d_{14}; p_7$) could be received when transmitting [111101110]. The syndrome S will be given by:

$$S = Y_1 H^T = [1 \ 1 \ 1 \ 0 \ 0 \ 1 \ 1 \ 1 \ 0] H^T = [1110] \quad (12)$$

Applying the corrective action (Table 3) the fourth bit, the violet, has an error and has to flip to recover the original message. The syndrome could be the same even if the two code words are different. When $S_1=1$, $S_2=1$, $S_3=1$ and $S_4=0$, we notice that bit v (violet) appears in the computations for S_1 , S_2 and S_3 (10), so, v is the sole candidate as the bit with the error.

Combining the information given by the generated parity bits and signal levels either the absence or the presence of one error will be easily checked, even for similar values of the different MUX levels. This correction is obvious from the MUX signal under back irradiation (Fig. 2) where data have shown that the MUX signal is strongly enhanced if the violet bit is in the *on* state, allowing confirmation of the presence of the violet bit if generated.

Results show that by using a pin/pin optical processor under steady state irradiation and simultaneously storing the MUX signal due to the received data code and generated parity, consecutive levels in the data code (RGBVI) do not correspond to two near levels in the parity levels [P_R , P_G , P_B , P_V]. For instance, in the message [001001010] (d_2 ; p_{10}) the level d_2 is too near from d_1 level and an error could occur when decoding and the received message could result in [d_1 ; p_{10}]. The syndrome obtained was [0100] that corresponds to an error in the p_G that has to flip from 0 to 1 which corresponds to the level p_{14} what is obviously wrong. Nevertheless, the parity is correct (p_{10}) so, the error comes from the level that should be d_2 [00100].

5.3. Decoding Algorithm

In order to automate the process of recovering the original transmitted data an algorithm was developed and implemented. The transmitted information is decoded by comparing the MUX signal from the code with the simultaneous parity MUX signal under front irradiation, as shown in Fig. 4 and Fig. 5.

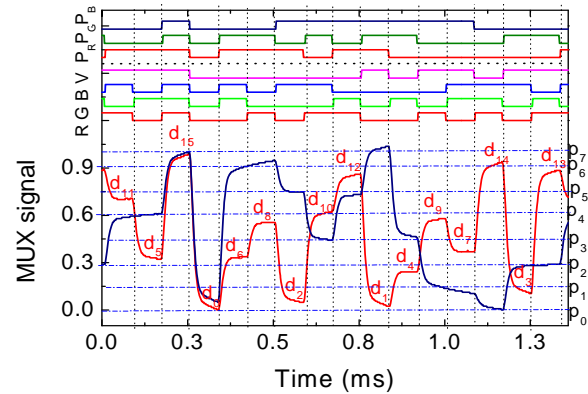


Fig. 4. Code and parity MUX/DEMUX signals under 390 nm front irradiation. On the top the decoded 7-bit word code [R G B V Pr Pg Pb] are shown.

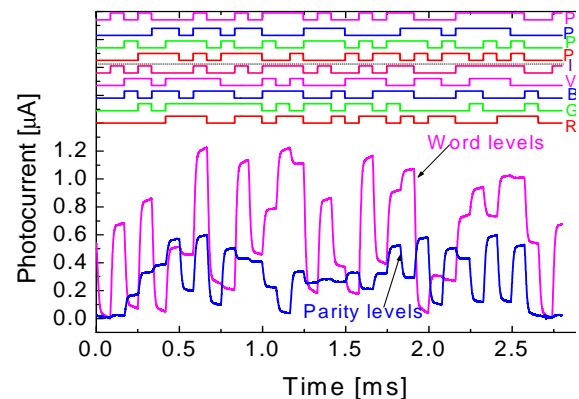


Fig. 5. Code and parity MUX/DEMUX signals under 390 nm front irradiation. On the top the decoded 9-bit word code [R G B V I Pr Pg Pb Pv] are displayed.

The decoding algorithm is based on a proximity search [16] after each time slot is translated to a vector in multidimensional space. The vector components are determined by the signal currents I_1 and I_2 , where I_1 (d levels) and I_2 (p levels) are the currents measured simultaneously under front optical bias for the 4-bit codeword (RGBV) in a four channel transmission or 5-bit codeword (RGBVI) if five channels are used for the word transmission. The correspondent parity levels, [P_R , P_G , P_B] or [P_R , P_G , P_B , P_V] in the respective time slot are also obtained and are assumed to be correct. The result is then compared with all vectors obtained from a calibration sequence (Fig. 3) where to each code level, $d_{(0-31)}$, is assigned the correspondent parity level, $p_{(0-15)}$. The colour bits of the nearest calibration point are assigned to the time slot. An Euclidian metric is applied to measure the distances.

We have tested the algorithm with different random sequences of the channels and we have recovered the original colour bits, as shown in the top of Fig. 4 and Fig. 5.

For simplicity and to guide the eyes, in Fig. 4, for the simultaneous transmission of the data word and parity code (RGBV: P_R, P_G, P_B), for each time slot, the received data (d_{0-15} levels) is marked in the correspondent MUX slots as well as the received parity levels (p_{0-8}) marked as horizontal lines. On the top of both figures the decoded 7-bit coded word (Fig. 4) or the decoded 9-bit coded word (Fig. 5) is exhibited [17].

6. Conclusions

Based on a-SiC:H technology, we presented an optical processor for data error detection and correction using a suitable (9,5) Hamming binary code generator and the syndrome decoding process.

Results show that by comparing the MUX signal due to the received data code word with the generated parity MUX signal, two consecutive levels in the data code (RGBVI) do not correspond to two near levels in the parity levels [P_R, P_G, P_B, P_V] allowing information retrieval.

The generator matrix, the parity check matrix and corrective action for each combination of the syndrome bits depends on the optical gain of both transmitted message and parity bits under lighting irradiation. An algorithm to decode the received data is presented and tested.

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