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Abstract. Orthogonal on–off keying (O^3K) is a coded modulation technique, where the input digital signal is mapped into a block of orthogonal codes. The encoded data, which is in orthogonal space, modulates the laser beam by means of O^3K. At the receiver, two photocells are cross coupled to compensate for the sunlight and other atmospheric noise. Since the laser beam is highly directional and can only be acquired by one photocell, the input laser signal can then be received with little noise, and signal processing is made easier. These techniques are especially beneficial in high bandwidth, long distance secure laser communication applications, such as for use in unmanned aerial vehicles. [DOI: 10.1117/1.OE.52.9.096113]

Subject terms: laser; communications; noise compensation; channel coding.

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1 Introduction

During the last two decades, there has been an explosive growth in the telecommunications industry.[1–5] With the addition of more and more individual computing devices, there will continue to be an exponential increase in demand, putting the existing wireless network resources under extreme pressure. Since bandwidth is scarce and therefore expensive in the typical wireless communication system, alternate techniques, such as laser-based communications, are highly desirable. Free-space laser communications provide wide bandwidth and high security capabilities to unmanned aircraft systems in order to successfully accomplish intelligence, surveillance, target acquisition, and reconnaissance missions.[6,7] For this application, an optical receiver is a critical component and needs to be designed to operate in sun light and other ambient noise environments while providing reliable data transmission. Current optical receivers use optical filters, colored and neutral density filters, and low-, band-pass, and high-pass filters. Some receivers do not have any kind of filtering and use computers to sift through all the signals to receive the correct one. All of these have the effect of reducing signals from unwanted bandwidths while keeping others, and when they are placed with photodiodes, are often called "daylight" filters. None of these truly cancel out all ambient signals; they only diminish the power of the unwanted bandwidth.

In this article, a technique based on orthogonal on–off keying (O^3K) along with a differential optical receiver is presented for free-space laser communication. O^3K is a coded on–off keying modulation that utilizes a block of biorthogonal code to map a block of data.[8] In this scheme, when a block of data needs to be transmitted, the corresponding block of biorthogonal code is transmitted by means of on–off keying. At the receiver, two photodiodes are cross coupled. The effect is that the net output power is close to zero.[9] The laser signal is then transmitted only into one of the receivers. With all other signals being canceled out, the laser signal is an overwhelmingly dominant signal. In the proposed configuration, two signal generating photoreceptors are arranged such that when they are opposed to one another, the effect is a cancellation, if and only if the both photoreceptors receive the same amount of input. The detailed design and bit error performance are presented to illustrate the concept.

2 Orthogonal On–Off Keying

2.1 *Rate 1/2 O^3K Modulation*

Orthogonal codes are essentially (n, k) block codes where a k-bit data set is represented by a unique n-bit orthogonal code ($k < n$). We illustrate this by means of an 8-bit orthogonal code, having 8-orthogonal and 8-antipodal codes for a total of 16 biorthogonal codes. This is shown in Fig. 1. Here, the input serial data is inverse multiplexed into four-parallel streams. These bit streams, now reduced in speed by a factor of 4, are used to address sixteen 8-bit biorthogonal codes, stored in an 8×16 read only memory (ROM). The output of each ROM is a unique 8-bit orthogonal code, which is then modulated by means of O^3K that are modulated and transmitted through the optical channel.

If the input bit rate is defined as R_b (bits/s), the code rate can be readily obtained as

$$r = 4/8 = 1/2. \tag{1}$$

The transmission bandwidth will be given by

$$\mathrm{bw} \approx \frac{8}{4} R_\mathrm{b}\mathrm{Hz} = 2R_\mathrm{b}\mathrm{Hz}. \tag{2}$$

According to channel coding, this scheme is essentially rate 1/2 coding and it can correct one error.

2.2 *Rate 3/4 O^3K Modulations*

A rate 3/4 orthogonal coded modulation with $n = 8$ can be constructed as shown in Fig. 2. Here, the incoming high-speed data, R_b (bits/s), is demultiplexed into six-parallel

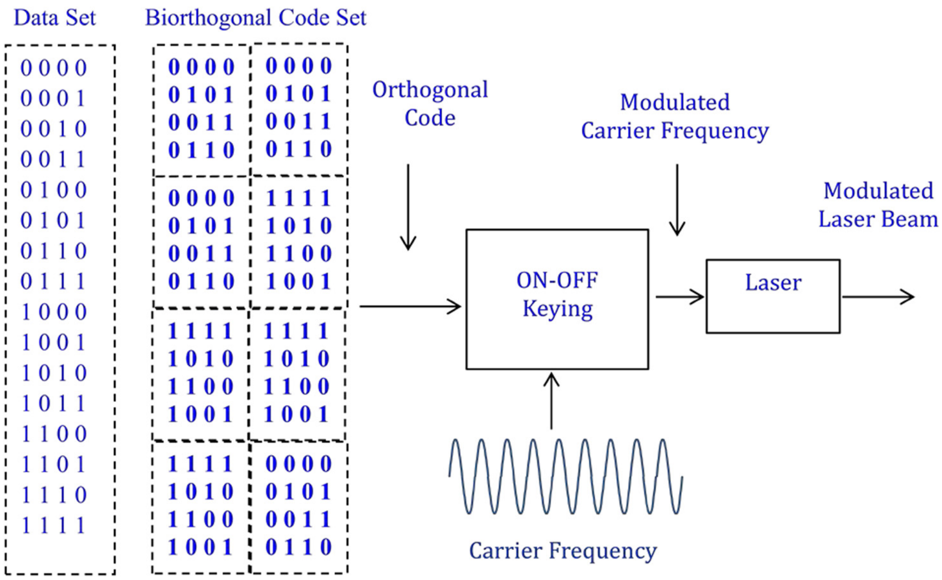

Fig. 1 Rate 1/2 orthogonal coded on–off keying modulation with $n = 8$.

streams ($k = 6$). These bit streams, now reduced in speed to $R_b/6$ (bits/s), are partitioned into two subsets, 3-bits per subset. Each 3-bit subset is used to address eight 8-bit orthogonal codes. These codes are stored in two 8×8 ROMs. The output of each ROM is a unique 8-bit orthogonal code, which is then modulated by the respective modulators, combined and transmitted through the optical channel.

The transmission protocol is such that when a 3-bit data set needs to be transmitted, the corresponding 8-bit orthogonal code is transmitted. Since each signal stream is now in orthogonal space, they can be expressed as a linear combination of two noninterfering signals. The transmission bandwidth is given by

$$\text{bw} \approx \frac{8}{6} R_\text{b} \text{Hz}. \quad (3)$$

The code rate is obtained as $r = 6/8 = 3/4$.

3 Decoding Principle

The output of the demodulator is a unique orthogonal (antipodal) code, which is first examined by generating a parity bit. If the parity bit is one, the received code is said to be in error. The impaired received code is then compared to a look-up table for a possible match. Once the closest approximation is achieved, the corresponding data is outputted from the look-up table. A brief description of the decoding principle is given below.

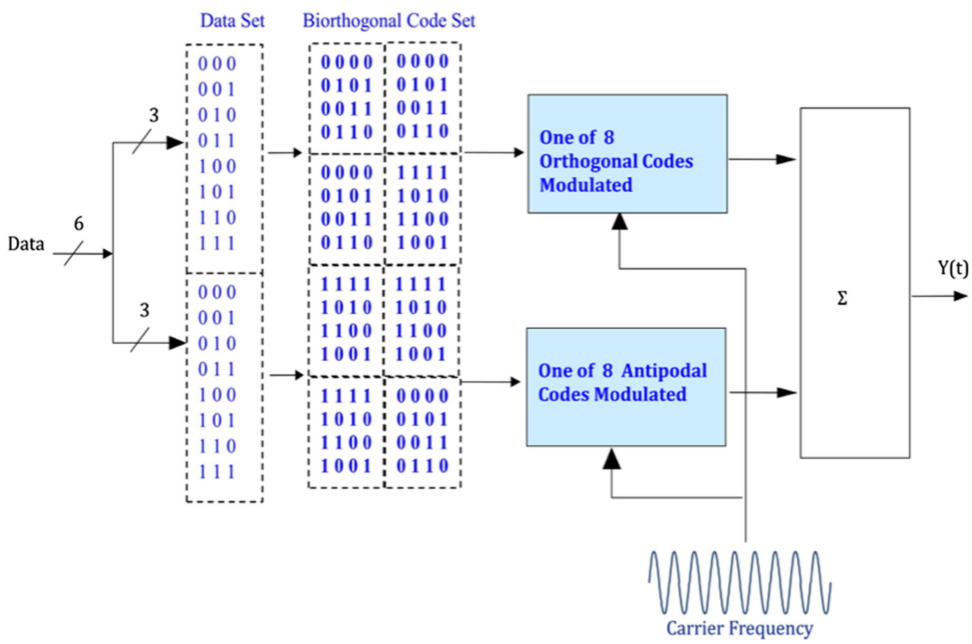

Fig. 2 Rate 3/4 orthogonal coded modulation with $n = 8$.

An n-bit orthogonal code has $n/2$ 1s and $n/2$ 0s; i.e., there are $n/2$ positions where 1 s and 0 s differ. Therefore, the distance between two orthogonal codes is $d = n/2$. This distance property can be used to detect an impaired received code by setting a threshold midway between two orthogonal codes as shown in Fig. 3, where the received coded is shown as a dotted line. This is given by the following equation:

$$d_{\mathrm{th}} = \frac{n}{4}, \tag{4}$$

where n is the code length and d_{th} is the threshold, which is midway between two orthogonal codes. Therefore, for the 8-bit orthogonal code (Fig. 4), we have $d_{\mathrm{th}} = 8/4 = 2$. This mechanism offers a decision process, where the incoming impaired orthogonal code is examined for correlation with the neighboring codes for a possible match.

The acceptance criterion for a valid code is that an n-bit comparison must yield a good autocorrelation value; otherwise, a false detection will occur. The following correlation process governs this where an impaired orthogonal code is compared with a pair of n-bit orthogonal codes to yield

$$R(x, y) = \sum_{i=1}^{n} x_i y_i \leq \frac{n}{4} - 1, \tag{5}$$

where $R(x, y)$ is the autocorrelation function, n is the code length, and d_{th} is the threshold as defined earlier. Since the threshold (d_{th}) is in the midway between two valid codes, an additional 1-bit offset is added to Eq. (4) for reliable detection. The average number of errors that can be corrected by means of this process can be estimated by combining Eqs. (3) and (4), yielding

$$t = n - R(x, y) = \frac{n}{4} - 1, \tag{6}$$

where t is the number of errors that can be corrected by means of an n-bit orthogonal code. For example, a single-error-correcting orthogonal code can be constructed by means of an 8-bit orthogonal code ($n = 8$). Similarly, a three-error-correcting, orthogonal code can be constructed by means of a 16-bit orthogonal code ($n = 16$), and so on. Table 1 shows a few orthogonal codes and the corresponding error-correcting capabilities.

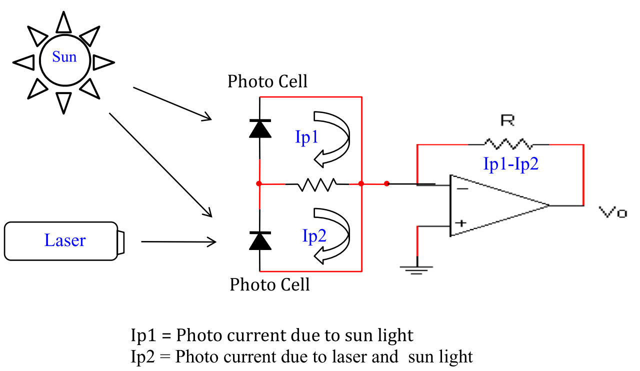

Fig. 3 Differential laser receiver. Illustrating sun light cancellation.

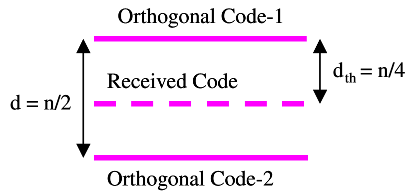

Fig. 4 Decoding principle. The received code is compared to a look-up table for a possible match.

4 Error Performance and Coding Gain

In the previous section, we have established that an n-bit orthogonal code can correct t errors, where $t = (n/4) - 1$, n being the code length. A measure of coding gain is then obtained by comparing the word error without coding WER (U) to the word error with coding WER (C). We examine this by means of the following analytical means.[10,11]

Let a k-bit data set be represented by an n-bit orthogonal code, where $n > k$. Then, the code rate will be k/n and the coded bit rate will be $R_c = (n/k)R_b$, where R_b is the uncoded bit rate. Since $n > k$, the coded bit rate R_c will be greater than the uncoded bit rate R_b ($R_c > R_b$). Consequently, the coded bit energy E_c will be less than the uncoded bit energy E_b ($E_c < E_b$). If S is the transmit carrier power, then the uncoded bit energy (E_b) and the coded bit energy (E_c) will be

$$E_b = \frac{S}{R_b} \tag{7}$$

$$E_c = E_b\left(\frac{k}{n}\right) = \left(\frac{S}{R_b}\right)\left(\frac{k}{n}\right). \tag{8}$$

With $\mathrm{O^3K}$ modulation and noncoherent detection, the uncoded bit error probability P_{eu} and the coded bit error probability P_{ec} over additive white Gaussian noise (AWGN) channel without fading are given by

$$P_{\mathrm{eu}} \approx \frac{1}{2}\,\mathrm{Exp}\left(\frac{-E_b}{2N_0}\right) = \frac{1}{2}\,\mathrm{Exp}\left(\frac{-S}{2R_b N_0}\right), \tag{9}$$

Table 1 Orthogonal codes and the corresponding error correction capabilities.

Code length n	Number of errors corrected t
8	1
16	3
32	7
64	15

$$P_{ec} \approx \frac{1}{2} \text{Exp}\left(\frac{-E_c}{2N_0}\right) = \frac{1}{2} \text{Exp}\left[\left(\frac{-S}{2R_b N_0}\right)\left(\frac{k}{n}\right)\right], \quad (10)$$

where E_b/N_0 is the energy per bit to noise spectral density. E_b/N_0 is related to signal to noise (S/N) ratio, also known as "SNR" as follows:

$$\frac{E_b}{N_0} = \left(\frac{S}{N_0 R_b}\right) = \left(\frac{S}{N}\right)\left(\frac{W}{R_b}\right). \quad (11)$$

S/N is the ratio of average signal power to average noise power, where $N = N_0 W$, $W =$ signal bandwidth. E_b/N_0 is the normalized measure of the energy per symbol to noise power spectral density. The parameter E_b/N_0 is generally used to estimate the bit error rate (BER) performance of different digital modulation schemes.

Since $n > k$, the coded bit error will be more than the uncoded bit error. However, it still remains to be seen whether there is a net gain in word error rate due to coding. This can be achieved by comparing the uncoded word error rate WER (U) with the coded word error rate WER (C). These word error rates over AWGN channel with no fading are given by

$$\text{WER(U)} = 1 - (1 - P_{eu})^k, \quad (12)$$

$$\text{WER(C)} = \sum_{i=t+1}^{n} \binom{n}{i} P_{ec}(1 - P_{ec})^{n-i}, \quad (13)$$

where P_{eu} is the uncoded BER, P_{ec} is the coded BER, and t is the maximum errors corrected by the code. For a rate 1/2 orthogonal codes, the WERs for O^3K modulation were calculated for various code lengths and plotted in the graph as shown in Fig. 5. Coding gain is the difference in E_b/N_0 between the uncoded and the coded word error. Notice that at least 3 to 7 dB coding gains are available in this example. We also note that coding gain increases for longer codes. From these results, we conclude that orthogonal codes offer coding gain. Also, rate 1/2 and rate 3/4 are also available in the proposed scheme.

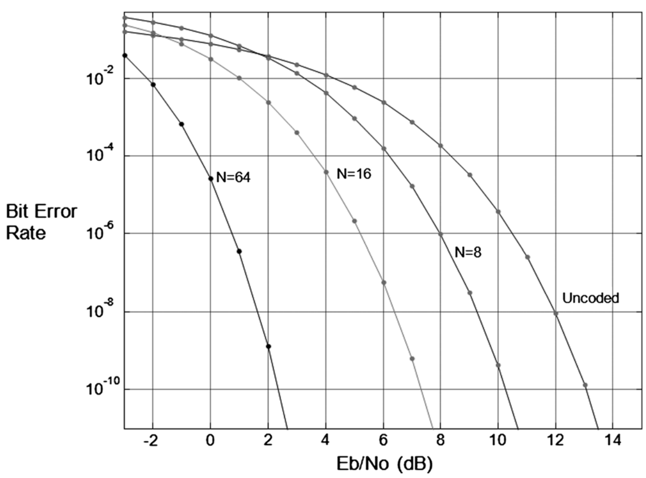

Fig. 5 Word error performance.

5 Ambient Light Cancellation

Current optical laser receivers, in their most basic construction, consist of one photodetector. In the absence of any kind of filtering, sunlight will produce a strong DC current. Strong sunlight will indeed overpower a laser signal, which may have been transmitted from a great distance. All ambient light, including sunlight, will produce an unwanted photocurrent, which is not due to the laser signal. Discerning a laser signal is difficult amid all the background noise received by the photodetector. Current filters are simply not good enough to eliminate all the unwanted noise, including sunlight. Therefore, a solution is needed to eliminate all of the unwanted signals.

In the proposed method, two photoreceivers are cross coupled as shown in Fig. 3. The effect being that the net output power is zero or close to zero (Fig. 3).[9,12] The laser signal is then transmitted only into one of the receivers. With all other signals being canceled out, the laser signal is an overwhelmingly dominant signal, which is then demodulated and decoded by means of code correlation.

6 Real-Time Measurement

The real-time measurement of the laser signal was based on LABVIEW. The receivers used in the experiment were solar panels: One pair is manufactured by Sanyo Energy, model number AM-1801CA, 53×25 mm^2, and another pair is manufactured by Parallax Inc., model number 750-00030, 125×63 mm^2. There were two lasers used, a 532-nm laser (green), model number CPA-LP0080-2 and the white light from an Illumin laser keychain light, model ESP 006. The laser transmitter is held securely and the results were collected using a National Instruments myDaq connected to a laptop computer. A 1-kHz sine wave was generated using a K & H IDL-800 Digital Lab and transmitted via laser and white light emitting diode (LED). The power of the frequency components of the total incoming signal was examined for two cases: with and without cancellation using photoreceivers.

Figure 6 shows the result for the green laser modulated at 1 kHz when there is only one receiver, as in conventional systems, and Fig. 7 is with the same input but with two receivers in cancellation mode. We can see immediately that the 1-kHz component is stronger for the case when

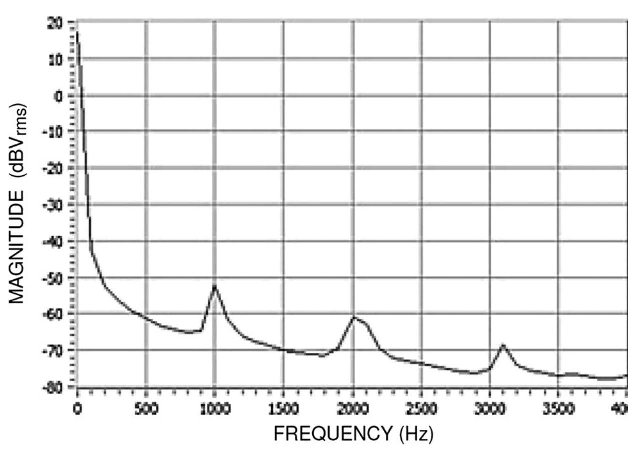

Fig. 6 Real-time measurement with a single receiver.

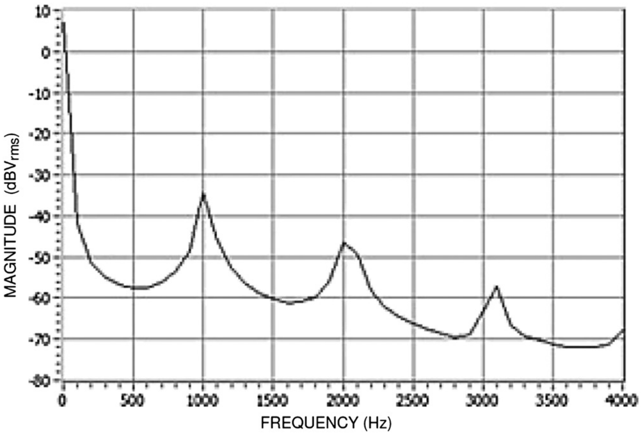

Fig. 7 Real-time measurement illustrating sun light cancellation with two receivers cross coupled.

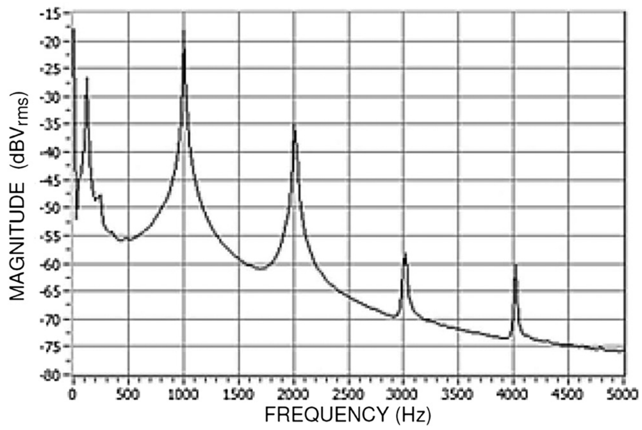

Fig. 9 Real-time measurement illustrating indoor light cancellation with two receivers cross coupled.

there are two receivers cross coupled. The increase is from −52 dB, to about −35 dB, a roughly seven times gain. The harmonics have also increased in power (the sine wave was apparently not perfect). Most importantly, the sunlight component (around 0 dB) has decreased from 18 to 8 dB, a three times decrease in the magnitude of ambient light.

We see a similar result with the white light (which was used because it is unencumbered by the protection circuitry of the laser) LED in Figs. 8 and 9. Here, we see that the 120-Hz component from the light bulb has decreased in magnitude by a factor of 6 when there is cross coupling. Most striking is the improvement in the 1-kHz signal, the quality of which has improved and the magnitude of which has increased; the signal is three times stronger when there is cross coupling as opposed to a single receiver as in conventional systems.

We can see in this case that cross coupling two receivers not only reduces ambient light (in this case, light bulbs) but also increases the gain from our intended signal (the white light covered the entire panel, whereas the green laser did not, so the effect of cancellation may be different on these two methods of input). We see that cross coupling two photoreceivers serves and cancels out any common signal input. The input signal is relatively stronger compared to all other signals in differential mode when compared to a single photoreceiver only.

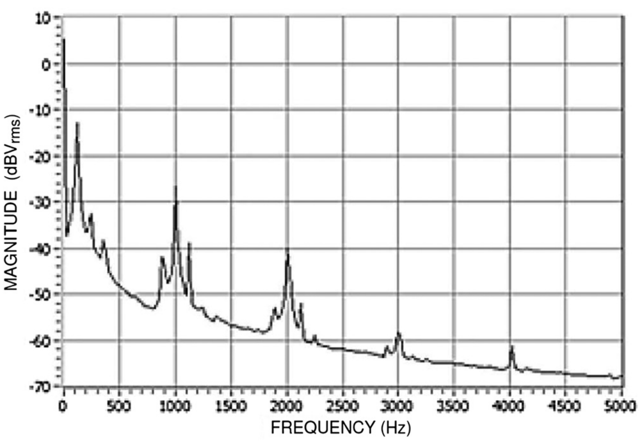

Fig. 8 Real-time measurement with a single receiver.

This differential photoreceiver can be used in free-space and deep-space laser communications, where sunlight and other atmospheric noise are problems. Techniques to increase the bandwidth by eliminating the parasitic capacitance of the solar cell can also be accomplished.

7 Conclusions

A technique based on O^3K along a differential optical receiver is presented for free-space laser communication. O^3K is a coded on–off keying modulation that utilizes a block of biorthogonal code to map a block of data. The transmission protocol is such that when a block of data needs to be transmitted, the corresponding block of biorthogonal code is transmitted by means of on–off keying. A performance analysis of the modulation technique demonstrated a 3 to 7 dB coding gain. At the receiver, two photocells are cross coupled resulting in a differential optical receiver. The effect is that the net output power due to sun light and other atmospheric effects are close to zero. Since the laser signal is highly directional, only one photocell responds to the laser signal. The laser signal is then transmitted only into one of the receivers. With all other signals being canceled out, the laser signal is an overwhelmingly dominant signal. The resulting signal has a significantly higher signal to noise ratio, avoids sensor saturation by sunlight, and eliminates the need for inefficient filters. The techniques presented enhance secure laser communication links for many applications in the telecommunication industry.

Acknowledgments

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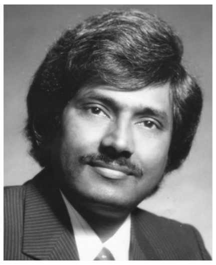
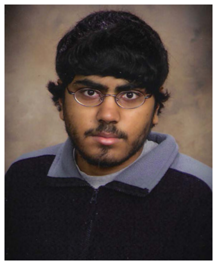


Saleh Faruque received MSc and PhD degrees in electrical engineering from University of Waterloo, Ontario, Canada, in 1976 and 1980, respectively. Upon completion of his degrees, he worked for telecom industries for more than 20 years in various capacities. At present, he is an associate professor, Department of Electrical Engineering, and University of North Dakota, Grand Forks, North Dakota. In 2011 to 2012, he was the recipient of the US Fulbright scholarship to Bangladesh. In addition, the College of Engineering and Mines, UND, awarded him the outstanding professor of the year 2007 to 2008 as well as in 2011 to 2012. He has authored one book and contributed chapters in three books. He has published over 75 papers in various technical journals and conference proceedings. In addition, he has secured 15 US and 3 Canadian patents. He is a life senior member of the IEEE.



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