Laser Based Underwater Communication Systems

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ABSTRACT

We report on recent progress in the field of visible light communications including direct modulation of blue laser devices at data rates beyond 10 Gbit/s, and the transmission of 2.5 Gbit/s OOK data through water. We also discuss the advantages of operating with single mode laser devices and matched filtering at the receiver in the context of applications with significant solar background. The system performance for two types of direct-detection receivers, a PIN detector and less conventional silicon Photomultiplier technology will be presented.

Keywords: visible lasers, frequency modulation, optical communication, oceanic optics, wavelength filtering devices, Fraunhofer line.

1. INTRODUCTION

The underwater world covers 70% of our planet, thus the ability to transmit data between vehicles and equipment underwater is a technology with a wide range of applications: underwater sensor networks (UWSNs), remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). One attractive option for underwater optical communications systems (UOCS) is underwater free-space optical (FSO) communication, which refers to an underwater optical link that uses water as the propagation medium. Recent developments of high bandwidth GaN [1] based sources within the low loss transmission window of water at visible wavelengths have led to a renewed interest in the development of UOCS using visible light for communication (VLC).

Laser based VLC with direct NRZ-OOK has shown data rates of up to 4 Gbit/s [1,2] and by taking advantage of more complex modulation schemes like OFDM it is possible to reach 9 Gbit/s [3]. We experimentally demonstrate high data rates over a free space link, NRZ-OOK (4.7 Gbit/s) and 64-QAM OFDM (11.9 Gbit/s), using direct modulation schemes of a 450 nm InGaN laser diode and a receiver with an optical -3 dB bandwidth of 1.4 GHz. An underwater optical tracking system and data transmission of 2.5 Gbit/s OOK through water is also reported [4]. The performance improvement given by solar background rejection in an oceanic scenario is modelled for a single mode laser matching a Fraunhofer line for different receiver configurations.

2. ABOVE WATER DATA TRANSMISSION

The above water FSO communication experiment was conducted using a commercially available laser diode with a nominal emission wavelength of 450 nm. The temperature stabilization was obtained with a Peltier thermo-electric cooling pad and a temperature controller in order to minimize the shift in transmitted wavelength and to keep the efficiency constant throughout the experiments. The threshold current of the device was 25 mA (threshold voltage 4.29 V) at 16.6 °C and the laser beam was collected and collimated with a microscope lens before being transmitted over a 15 cm free space link. The optical spectra of the InGaN laser exhibited the typical Fabry-Perot red shift in wavelength with increasing current, since the Burstein-Moss effect is small in GaN based device [5]. The maximum optical bandwidth of the system was obtained by varying the drive current (from 54.1 mA to 107.1 mA) for each bit rate. A pseudo random bit sequence (PRBS) pattern was combined, via a bias-T, with the laser beam and this was focused onto the silicon PIN photo-receiver. The quality of the received pattern was evaluated from the analysis of the eye-diagram, using a digital sampling oscilloscope and from the BER value on the detector. The required optical power, varied by using a neutral density filter, to achieve a BER of 1×10^{-9} at 1.5, 2, 3, and 4.7 Gbit/s was, respectively, -18.81, -16.90, -14.20 and -7.37 dBm as shown in Fig. 1(a).

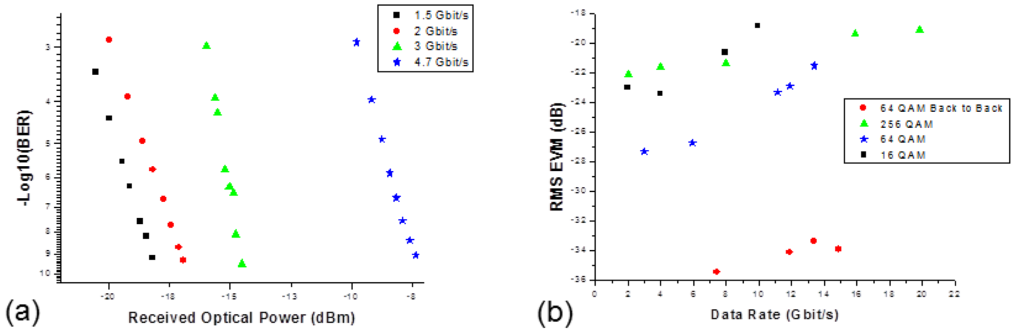

Figure 1: (a) BERs vs. received optical power at 1.5, 2, 3 and 4.7 Gbit/s at optimum bias currents for each bit rate; (b) RMS EVM magnitude at 256QAM, 64QAM and 16QAM. 64QAM back to back shows instrument noise.

An additional 1.61 dB power penalty was measured when increasing the operating frequency from 1.5 to 3 Gbit/s due to the limiting performance of the receiver. Maintaining the same set-up, the advantage of the M-QAM OFDM modulation scheme was evaluated substituting the PRBS generator with a Tektronix arbitrary wave generator (AWG70001A) and the BER detector for a Tektronix digital oscilloscope (MSO73304DX). The M-QAM order was varied from 16 to 256 and the resulting data rate versus RMS Error Vector Magnitude (EVM) are reported in Fig. 1(b). As reported in [6], the FEC criterion derived maximum BER of 3.8×10^{-3} was satisfied at data rates of 9.92 Gbit/s and 11.9 Gbit/s for 16 and 64 QAM respectively. For higher modulation formats the required EVM for the maximum BER were not achieved due to a combination of instrument and system noise. There was no data transmission at 256 QAM that satisfied the FEC limit due to the greater SNR required for 256 QAM. Nevertheless, we report a gain of around 8 times the native bandwidth by the use of OFDM modulation formats without the use of an adaptive bit loading. The main limitation was the frequency response of the detector which rolls off very steeply after the -3 dB point, resulting in an ineffective bit loading at high frequency.

3. BELOW WATER DATA TRANSMISSION AND LASER TRACKING

In this section the experimental analysis of the underwater laser tracking and data transmission performed by M.A. Watson *et al.* [4] using the water flume facilities at the University of Glasgow is summarised. The various GaN based laser diodes had a wavelength in the range 421 nm to 425 nm, which corresponds to the lowest water attenuation in the water type classed as oceanic clear [7]. In order to simulate the effects of increased water turbidity in a laboratory, Maalox antacid was used as a scattering agent in addition to fresh water. It consists mostly of $Mg(OH)_2$ and $Al(OH)_3$ with a very similar volume scattering function (VSF) to that of seawater. The extracted attenuation coefficient value for clear water was 1.2 m^{-1} and the communication link was established over a distance of 1 m, sufficient to investigate the effects of scattering on the laser beam even for high concentrations of Maalox (4 litres of Maalox in 8000 litres of water). The performance of an optical active tracking system was obtained by collecting the laser beam (optical power of ~30 mW) with a focussing lens in combination with a narrow band filter in front of a silicon quadrant photo-detector.

Even in clear water condition, the scattering level was still appreciable. At very high concentration of Maalox the laser beam is scattered away from the optical axis and the diameter increases, resulting in a reduced contrast between the centre of the beam and the wings. The result is a reduced optical intensity at the receiver end, down to the limit at which the tracking system ceased to operate (~5 parts Maalox in 10^4 parts water). The underwater data transmission was evaluated by modifying the experimental setup adding a PRBS of 2^7-1 bits to the device and replacing the quadrant photo-detector with the aforementioned silicon PIN photo-receiver over a path length of 1.7 m without the addition of Maalox. Figure 2 shows that the eye diagrams of the received signal visualized on the oscilloscope were still sufficiently open to resolve the pulses of the signal up to a data rate of 2.488 Gbit/s, despite the water attenuation and the limited bandwidth of the photo-receiver. The ability to distinguish the individual pulses within some distance from the optical axis provides evidence of the suitability offered by the implementation of a tracking system and/or a data receiver in a UOCS, particularly if arranged in arrays [8].

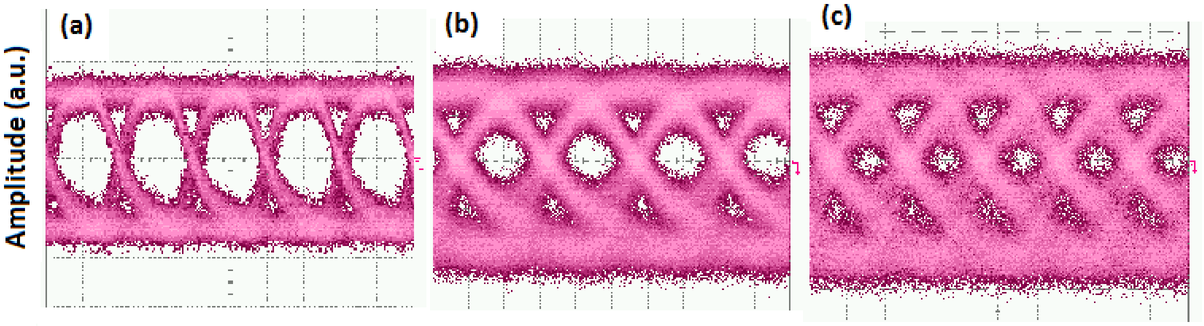

Figure 2. Eye diagrams showing data transmission for a signal transmitted through the water at (a) 1 Gbit/s at 125 mA laser drive current, (b) 2 Gbit/s at 132 mA and (c) 2.488 Gbit/s at 132 mA [4].

4. SUNLIGHT REJECTION

The overall performance of an UOCS depends on the signal detected from the optical source and on the amount of sunlight that falls on the receiver. A high-resolution solar spectrum has many narrow dark lines that correspond to Fraunhofer lines. These narrow wavelength intervals of relative intensity minima are natural filters that represent absorption lines due to the cooler outer layers of the Sun's atmosphere containing vaporized elements. It is reasonable to expect an advantage if an UOCS is operating within a Fraunhofer line, thanks to the reduced solar background [9]. There are three main regions of interest to a UOCS (434.05 nm, 486.13 nm, 518.36 nm) where the Fraunhofer lines are present. Since the minimum value of the attenuation coefficient is shifting from blue wavelengths to green as the turbidity is increasing from clear ocean to harbour water [7], the optimum Fraunhofer line can be selected according to the water type. Due to their narrow FWHM (from 0.1 nm to 0.3 nm) [10], a single mode laser device and matched filtering at the receiver are required. A solution would be the combination of a Fabry-Perot etalon and a multilayer dielectric filter on the receiver side. The etalon spacing has to be chosen so that it provides narrow band-passes with one corresponding to the centre frequency and width to the desired Fraunhofer line. Because even a thin etalon has many passbands, it is necessary to use a band-pass filter that is also centred on the same line and that blocks transmission at all the etalon passbands except the one of interest. A conventional interference filter can be replaced by a Lyot or birefringent filter (BRF), which uses a linear arrangement of birefringent elements and linear polarisers to transmit a narrow range of wavelengths. The BRF filter exhibits a decreased angular sensitivity compared to a conventional narrowband interference filter. For example, based on the equations given in [11], a 0.14 nm $LiNbO_3$ interference filter is estimated to have a FOV of ±2.3° while a $LiNbO_3$ birefringent filter of similar bandwidth would have a FOV of ±16.5°. The scenario of an unpolarised laser source of 1 mW located at the sea surface and pointing downward along the vertical axis where the upward-facing receiver, with an active area diameter of 2.5 cm and a -3 dB bandwidth of 25 MHz, is considered. It is assumed that a tracking system is used in the system, i.e. the laser beam is aligned with the receiver so that the angle between the optical axis of the receiver and the line of sight between them is zero. The simulations have been computed for different angles of incidence and the signal collected at several optical bandwidths is compared with the associated noise. The incident direct solar radiation is modelled as having a random phase and polarisation, since the sunlight is unpolarised and the diffuse sky radiation has negligible effects on the polarisation. The spectral density is constant across the frequencies transmitted through the optical bandpass filter (OBPF) at a single wavelength; hence it is reasonable and appropriate to draw an analogy between background radiation and white noise.

The inverse relation between the SNR and receiver FOV is investigated and summarized in Fig. 3 for a distance between transmitter and receiver of 5 m. When using a Fabry-Perot filter with a FOV comparable with a birefringent filter, there is negligible difference between a transmission wavelength that matches a Fraunhofer line and an adjacent one. This arises from the fact that the range of wavelengths over which the solar irradiance is collected is much wider than the FWHM of the Fraunhofer line. In this scenario the wide FWHM of the narrowband interference filter reduces the solar rejection benefit of operating within a Fraunhofer line in the optical communication. The larger collected background intensity results in a SNR that tends faster to the plateau value corresponding to the scenario when no filter is placed in front of the receiver. In contrast with an interference filter, the use of a birefringent filter does not entail a degradation of the overall SNR even for wide FOV. These findings are summarised in a gain up to 20 dB when using a birefringent filter in both the receiver configurations. The SNR profiles include the Fresnel reflections at the water-filter interface ($n_W = 1.3437$ and $n_F = 2.3503$ respectively). For normal incidence the loss is about 7.4% while it increases consistently at higher angles with a negative impact on the overall system performance.

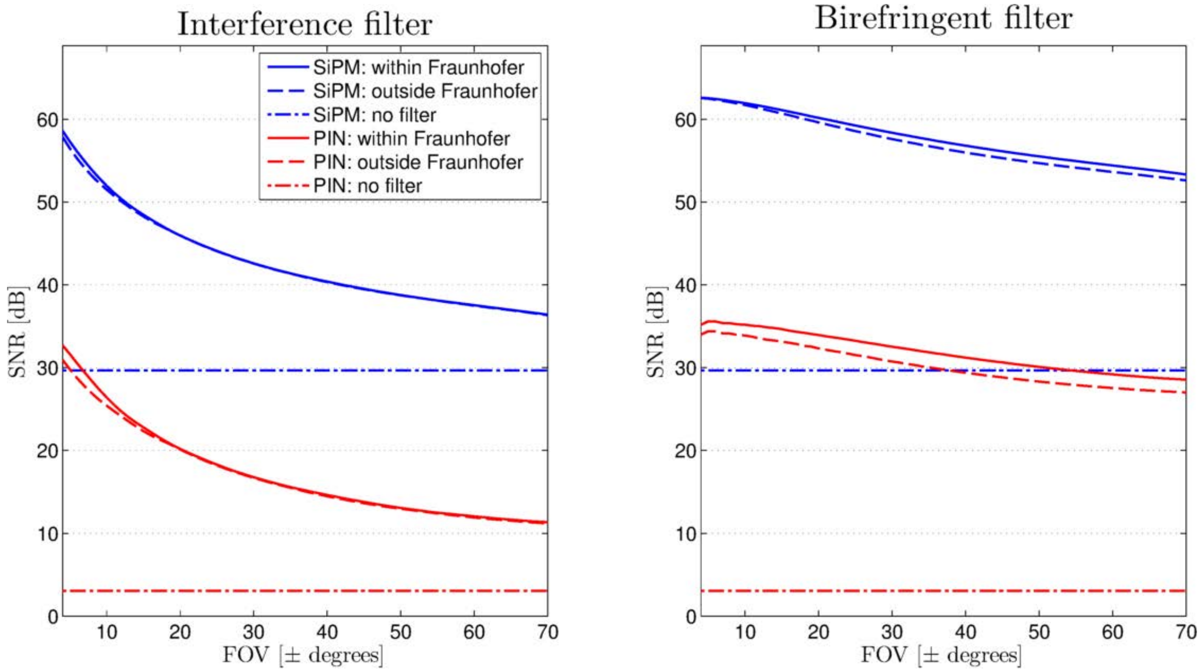

Figure 3. Comparison of the SNR profiles as function of the FOV at a depth of 5 m for various configurations at the receivers when adopting different filters.

The advantages of operating at a Fraunhofer line are less evident since most of the background noise is rejected by the narrow filter, with a slight improvement for a PIN receiver. The decreased angular dependence of a birefringent filter spectral characteristic with respect to a conventional interference filter results in a wider FOV and a better solar background rejection. It is worth noting that the impact of the background radiation is highly variable during the day and it depends on the link geometry. Then the highest improvement would be obtained when the receiver is most susceptible of the background light such as when facing upwards. In this case, the use of a birefringent filter could give a gain up to 20 dB compared to a more traditional interference filter. The greater SNR produced is the result of the high solar light rejection that is translated into communication at higher speeds. A reduction in the receiver aperture results in a reduced collection of the solar background radiation and in a shorter recharge time that would result in a higher bandwidth. The latter value, used in the simulation, is limited by the silicon Photomultiplier (i.e. 25 MHz) that can be considerably increased by using a PIN receiver at the expense of a lower SNR. In order to increase the SNR, it is necessary to introduce amplification of the incident optical power while maintaining the noise power associated at the detector as low as possible. Since an increase in temperature will modify the transmission filter and will increase the dark count rate as well as the breakdown voltage of the silicon photomultiplier, a thermoelectric cooler is required.

5. CONCLUSIONS

High data rate VLC using a GaN based laser diode has been portrayed. With an optical system bandwidth of 1.4 GHz, record data transmission rates have been demonstrated over a 15 cm free space link of 4.7 Gbit/s for NRZ-OOK and 11.9 Gbit/s for 64 QAM-OFDM. In order to realise these data rates below water, a high pointing accuracy and a collimated beam are required in order to maximise the power at the receiver and to extend the communication range. The collecting optics and the receiver aperture must therefore be carefully considered in the system design process. A reduction in the receiver aperture results in an increased geometric loss and a more challenging tracking operation. For short ranges a relatively wide OBPF may be adequate, whereas for longer ranges a narrow-linewidth single mode laser diode is required along with a high spectral discrimination using a narrow OBPF. Increasing the laser power or the receiver sensitivity will result in a higher SNR. In the current model of a UOCS only the optical attenuation due to the absorption has been considered. The major system parameters are indicative values and it is the intention to iterate the process in order to fine tune and make the necessary design trade-offs according to the specific scenario.

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