Optical communication for next generation chip on tip surgical endoscopes

Asif Newaz Khan*[1,2], Cleitus Antony[1,3], Meena Baskaran[4], Brian Corbett[4], Sanathana Konugolu Venkata Sekar[5], Ray Burke[5], Stefan Andersson-Engels[3,5], Paul D. Townsend[1,3]
[1]Photonics System Group, Tyndall National Institute, Cork, Ireland; [2]School of Engineering University College Cork, Cork, Ireland; [3]School of Physics, University College Cork, Cork, Ireland; [4]III-V Device Group, Tyndall National Institute, Cork, Ireland; [5]Biophotonics@Tyndall, Tyndall National Institute, Cork, Ireland

ABSTRACT

The next-generation chip-on-tip surgical endoscopes require small footprint (1-3 French), hyperspectral imaging capability for multi-biomarker quantification with high frame rate to reduce motion artefacts. These innovations demand high data rate links, which could require twisted-pair cables if transmitted electrically. To eliminate bulky electrical wiring, we propose an all-optical powering and communication chip at the distal end consisting of a monolithically series interconnected Photonic Power Converter and a reflective electroabsorption modulator (REAM) based on a p-i-n diode structure with an embedded multiple quantum well (MQW) absorber. Optical sources for the power generator and reflective modulator are provided remotely over optical fiber, thus removing the need to host power-hungry lasers at the distal tip. To simplify the overall design, the communication scheme takes advantage of the REAM's dual functionality as a modulator and detector. Here, we have used a commercial REAM designed to operate at 1550nm and a novel Time Division Duplexing (TDD) communication protocol to demonstrate bidirectional transmission at 500 Mb/s over a single-mode fiber on a benchtop in order to examine the feasibility of the scheme. We found that at shorter wavelength near the MQW band-edge, zero-bias operation of the REAM is possible and the required modulation voltage swing is reduced. Operating under zero-bias at 1520nm instead of 1550nm leads to negligible static energy consumption and about 47% reduction in dynamic energy consumption, reaching an 8dB extinction ratio. Additionally, at 1520nm, the photocurrent generation responsivity increases dramatically at zero-bias, allowing the Transimpedance Amplifier (TIA) to be removed from the receiver circuit. This results in reduced footprint and power consumption of the receiver front end circuit.
Keywords: Guidewires, Half-duplex communication, Time Division Duplex (TDD), Reflective Electro-absorption Modulator

1. INTRODUCTION

Medical technology is increasingly shifting towards minimally invasive approaches in an effort to lower trauma, reduce expenses, shorten hospital stay and improve diagnosis accuracy[1-3]. For instance, Coronary Artery Disease (CAD) is often diagnosed and treated using a minimally invasive procedure called the Percutaneous Coronary Intervention (PCI)[3]. This involves the use of a flexible guidewire to guide a catheter to the target artery where a balloon may be inflated to compress the plaque against the artery wall. Although PCI has been proven successful, improvement in the imaging technique can add significant value to the diagnostic information. The current PCI imaging technique provides two-dimensional (2-D) images of the coronary arteries based on X-ray fluoroscopy. Therefore, it provides inadequate information about the complex 3-D geometry of the stenosis[2,3]. Consequently, there is a need to develop miniaturized catheter-based systems, for example, with micro-cameras integrated onto the tip of guidewires with submillimetre diameter for probing deep within the body.

Power and data transmission capabilities at the distal end are necessary for integrating micro-cameras. This requires the use of electrical wires with proper shielding and characteristic impedance, especially when high data rates (hundreds of Mbps) are required for real-time imaging. This significantly increases the guidewire diameter and compromises its flexibility making an electrical wired approach unrealistic for this application. As a result, there is a shift towards optical fiber based power delivery and communication links for smart guidewires. Optical powering and communication links were previously proposed for ultrasound imaging capable catheters[1,3,4] and active position tracking systems[5]. These communication schemes used either a pair of vertical-cavity surface-emitting laser (VCSEL) and a photodiode[1] or a combination of VCSEL and electrical wires[3] to enable two-way communication. Therefore the schemes have some disadvantages in terms of power consumption, compromising guidewire flexibility and requiring larger footprint. These are all absolutely critical factors for this application, where the guidewire size is highly constrained by the small target occluded vessel size, and guidewire flexibility and tactility are of paramount importance for surgical guidance and control. In addition, minimizing power consumption for the communication link is a critical need. This is because optical power delivery is less efficient and more costly compared to electrical power delivery and is, in general, constrained by human safety considerations. So it is important to treat power at the distal end as a scarce resource prioritized to enable the main required function, namely surgical imaging, and to minimize the power consumption of the communication channel. An innovative way to address these issues involves the use of a dual functional photonic device as an optical transceiver in the distal end. Using such a device removes the need for separate laser and photodiode, reducing the number of devices in the distal end and also eliminates the use of splitters or different fibers or cables to separate the upstream (US – from the camera) and downstream (DS – to the camera) channels. Dual functional photonic devices have been previously demonstrated using VCSELs[6], Distributed-Feedback (DFB) and Fabry-Perot lasers[7]. These devices require very high reverse bias voltage and/or operating current making them unsuitable for a footprint and power limited application. It is apparent that for this application the choice of a dual functional photonic device ought to enable the displacement of power-hungry components such as lasers from the distal to the proximal end. In this paper we propose and demonstrate a novel power efficient and small footprint optical communication link designed to support real-time imaging based on the principle of Time Division Duplexing (TDD) and dual functional capability of an REAM operating at zero bias voltage. The scheme adopts a four core multicore fiber (MCF) to enable compact spatial separation of the powering and communication wavelength. A conceptual CAD model of the proposed guidewire is shown in Fig. 1.

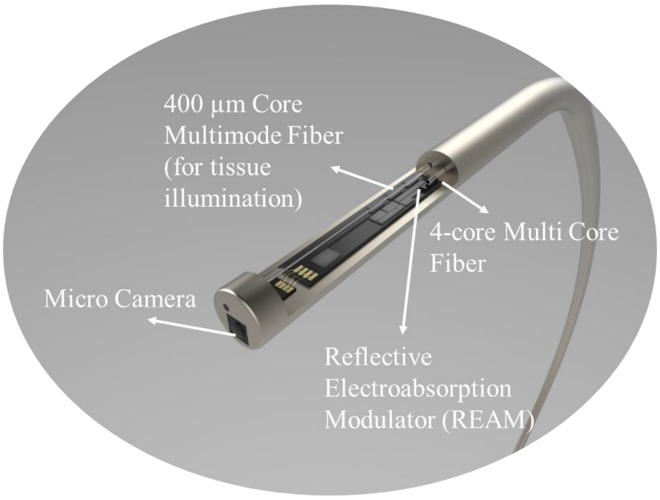

Figure 1. Conceptual CAD Model for illustrating the Reflective Electroabsorption Modulator and Multicore Fiber based guidewire system

2. LINK ARCHITECTURE

The link concept, shown in Fig. 2, takes into account the need to minimize both the footprint and power consumption of the optical transceiver at the distal end of the guidewire. The idea is to use a single core of the MCF and the same wavelength for both the downstream (DS - to camera) and the upstream (US - from camera) optical data channels while the other three cores are used for power generation using Photovoltaic (PV) cells. In contrast, conventional optical communication links use either two separate fibers or different wavelengths in a single fiber, for US and DS channel separation, both of which are impractical in this application due to the limited lateral area. Interestingly, the micro-camera requires bursts of control signals at ~1Mb/s to periodically update its settings and ~180 Mb/s (100 frames per second) for real-time image transfer. Therefore, simultaneous two-way communication is not required. This highly asymmetric traffic demand has allowed us to adopt a TDD based scheme sometimes referred to as "ping pong" in which US and DS data bursts are sent in different time slots, similar to an old fashioned "walkie talkie" radio.

The link utilizes the REAM's dual functionality as a modulator and detector. In the US frame, the MCF transfers continuous wave (CW) optical carrier from a laser at the proximal end to the REAM at the distal end. A Single Pole Double Throw (SPDT) switch is used to feed the camera image data signal into the REAM, which is used to modulate the amplitude of the incoming CW light. The amplitude modulated light is then reflected and fed back into the MCF by the reflective coating on the rear facet of the REAM and the intensity variation of the modulated light is finally detected in the proximal end using a photodiode. In the DS frame, the SPDT switch connects the REAM to the receiver circuit. The REAM receives amplitude modulated light representing the camera control signal from the proximal end and generates time varying photocurrent in response to the intensity fluctuation of the input light. The generated photocurrent flows to the receiver circuit where it is processed and fed into the camera. This novel feature of the REAM is appealing not just for footprint minimization but also for enabling the removal of a power hungry laser from the distal end.

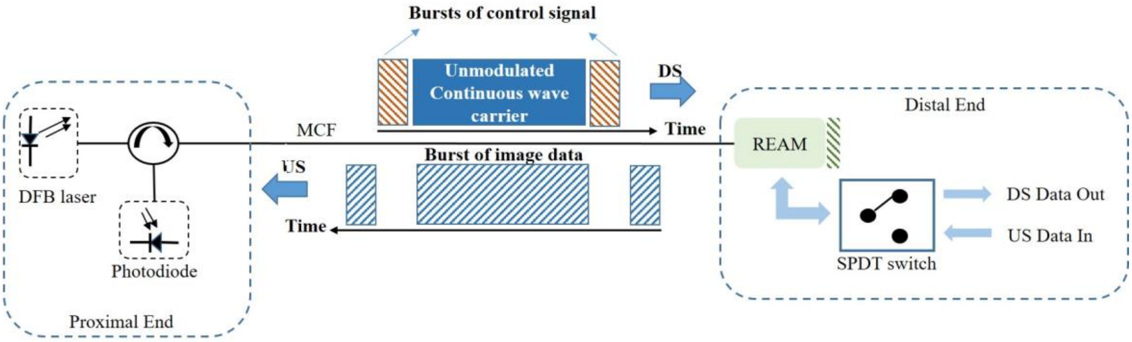

Figure 2. Proposed TDD and REAM based optical communication link

3. REAM BASED OPTICAL TRANSCEIVER

To evaluate the ability of an REAM to operate as an optical transceiver, i.e. as both a transmitter and a receiver, we first investigate the relevant properties and operating conditions using a commercial REAM. This device was designed solely as a modulator for transmitter applications, but here we investigate its potential for the dual function application. When an electric field is applied to the MQW structure there is a shift in the exciton absorption peak towards longer wavelength as seen in Fig. 3a. This shift in the exciton peak is known as the quantum-confined Stark effect. The change in the absorption coefficient with voltage at a fixed wavelength forms the basis of optical modulation and it is apparent that the applied voltage swing governs the extinction ratio which is one of the key characteristics of an optical modulator. Although the change in absorption coefficient is much more pronounced near the band-edge as seen in Fig. 3a it is important to investigate the optimum operating wavelength to obtain high extinction ratio while maintaining a reasonable insertion loss to ensure high Signal to Noise Ratio (SNR) at the receiver. The results in Fig. 3b highlight the change in extinction ratio and insertion loss with operating wavelength when the bias voltage of the REAM was switched between 0 and -2V. The extinction ratio was obtained by the difference in the reflected optical intensity for the change in the bias voltage. The insertion loss which includes both the coupling loss and the absorption of light in the material is measured from the reflected intensity of the higher modulation level (in this case 0V)[9]. From Fig. 3b, it is observed that operating wavelengths in the range of 1540 to 1560nm are suitable for optical modulation as they provide a reasonable insertion loss of less than 9dB and a very good extinction ratio of 10dB or higher when the bias voltage is switched between 0 and -2V.

To investigate the operation of the REAM as a detector we measured the responsivity and reflected optical intensity at 1550nm for various reverse bias voltages, the results are shown in Fig. 3c. For optical modulation, an REAM is usually biased at the maximum slope of the transfer curve (red curve in Fig. 3c) and for this particular device this point is at around -1.2V at 1550nm. At this bias voltage, the REAM shows moderate responsivity of around 0.5 A/W. However, it is obvious from Fig. 3c that the best photodetector performance (~0.65 A/W) can be achieved by increasing the reverse bias to -2V. These observations translate to an optimum operating wavelength of 1550nm with -1.2V bias and $2V_{pp}$

swing for modulation and -2V bias for receiver functionality. The change in bias voltage for receive mode will require an additional bias optimization circuit in the transceiver increasing the complexity, footprint and power consumption. On the other hand the high voltage swing required for modulation increases the demand on the distal end photovoltaics. In this power limited application it is important to ensure minimal power consumption while maintaining the device performance therefore it is important to study how the operating regime of an REAM governs the power consumption and look into power saving schemes.

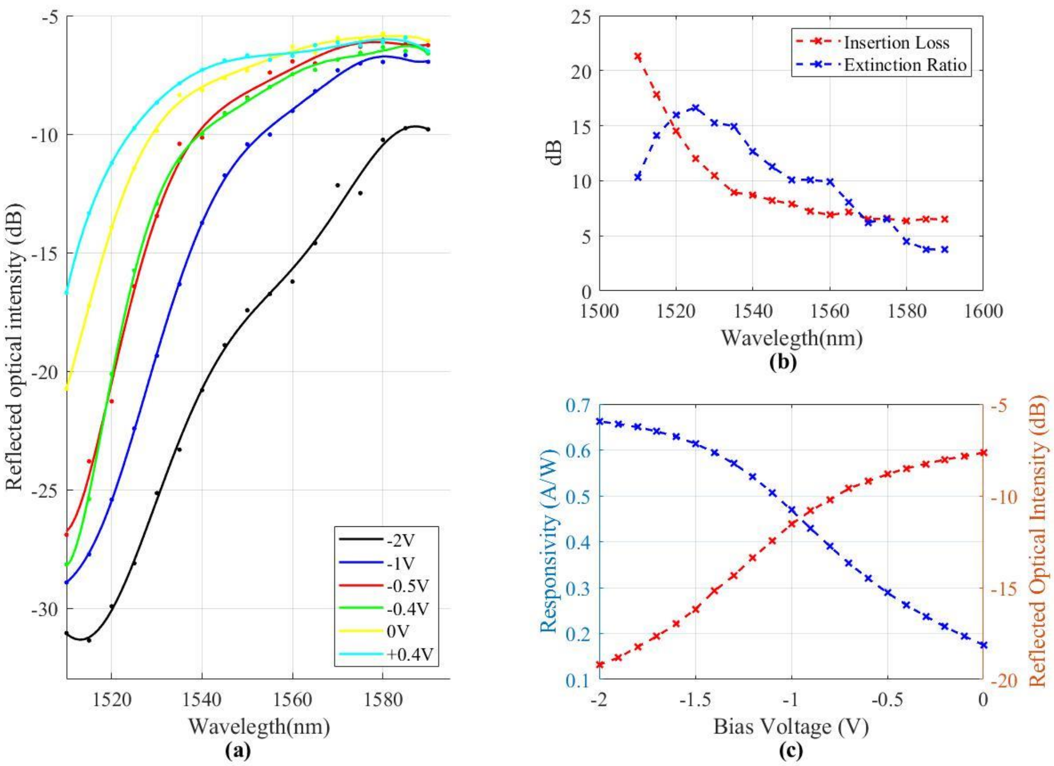

Figure 3 (a) Reflected Optical Intensity of the REAM under bias voltage in the range +0.4V to -2V. (b) Extinction Ratio and Insertion Loss when the bias voltage is switched between 0 and -2V. (c) Responsivity and Reflected Optical Intensity at 1550nm

3.1 REAM zero-bias operation and energy efficiency

The energy consumption of an EAM can be calculated by [10, 11]

$$E = \frac{1}{4} C V_{pp}^2 + \frac{I_{avg} V_{bias}}{B} \tag{1}$$

Here, the first term represents the dynamic energy consumption of an EAM with Capacitance, C for V_{pp} modulation voltage swing. The second term corresponds to the DC or static energy consumption at the bias voltage V_{bias} and the average generated photocurrent I_{avg} at a bit rate B. It is apparent that the energy consumption can be substantially reduced by reducing the modulation voltage swing sacrificing the extinction ratio. Similarly, the static energy consumption can also be minimized by reducing the bias voltage at a particular bit rate resulting in a lower responsivity. So it is important to determine the required device performance for this application.

In conventional long-haul links the optical link loss is high so it is desirable to have an extinction ratio of 10dB or higher and 0.8 A/W or higher responsivity to minimize the optical power penalty and attain appropriate receiver sensitivity for a given Bit Error Rate (BER) respectively. This is usually achieved using high bias voltage and modulation voltage swing. In contrast, it is reasonable to assume that for the proposed ultra-short link the received signal at the proximal end is far away from the thermal noise limit owing to very low optical link loss and the received optical power of the REAM is relatively high. Therefore, it is possible to trade-off the extinction ratio and responsivity to address the power constraint in the distal end while maintaining an error free link (BER < 10^{-9}). The tabulated figures in Table 1 illustrate a reasonable trade-off between the modulator and receiver characteristics of the REAM based transceiver and its power consumption. To evaluate the effect of operating conditions on the device performance and power consumption, the REAM is operated at various modulation voltage swing and input wavelength. The results are shown in Fig. 4.

Table 1 Required performance characteristics of the REAM based transceiver for the guidewire

Figure of Merits	Required Modulator Performance	Required Receiver Performance
Extinction Ratio	>5dB	-
Insertion Loss	≤15dB	-
Responsivity	-	>0.5A/W
Bias Voltage	<1V	<1V
Voltage swing	<1Vpp	-

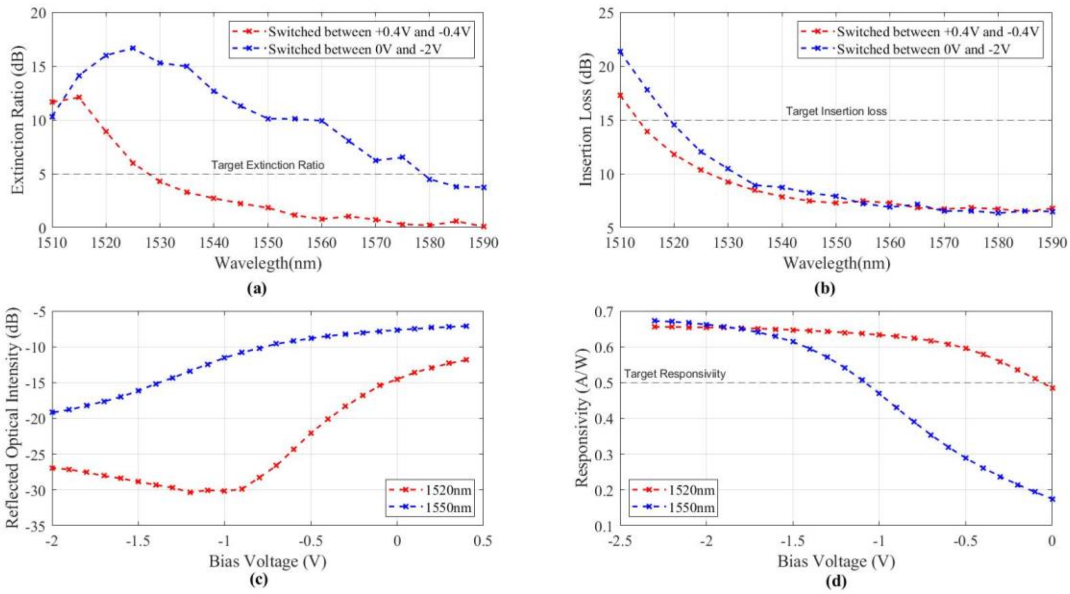

Figure 4 (a) Extinction ratio comparison. (b) Insertion loss comparison. (c) Reflected optical intensity of the REAM at 1520nm and 1550nm for various bias voltage. (d) Responsivity of the REAM at 1520nm and 1550nm.

It is seen from Fig. 4a that the extinction ratio substantially decreases for 0.8V swing compared to a 2V swing. However, the insertion loss shown in Fig. 4b is seen to improve due to the slight forward bias of the device. At 1520nm and 0.8V swing it is possible to achieve ~8dB extinction ratio and ~12dB insertion loss. These figures are acceptable for this short link where the power budget is not limited by the loss in the optical link. The origin of this behaviour is the strong wavelength dependence of the quantum confined Stark effect, which is apparent from the REAM transfer curves for 1520nm and 1550nm operating wavelengths shown in Fig. 4c. The 1520nm curve exhibits a steeper gradient which is shifted to a lower bias point compared to the curve for the nominal standard operating wavelength of 1550nm. This means the device requires a lower voltage swing to achieve the same extinction ratio at the shorter wavelength, albeit at the cost of a higher insertion loss. It is also seen from Fig. 4d that the responsivity of the zero-biased REAM at 1520nm is comparable to that achieved under 1.1V reverse bias at 1550nm. Thus dynamic energy saving of ~47% and negligible static energy consumption is possible by operating the REAM at shorter wavelength.

3.2 US link demonstration using zero-bias REAM

To compare the link performance the REAM is driven as a modulator at 500Mbps using 1550nm and 1520nm laser light with modulation voltage swings of 1.1Vpp and 0.8Vpp respectively emulating the US link as shown in Fig. 5. Approximately 8dB extinction ratio was calculated from the transfer curves of the REAM for the two wavelengths under investigation. The BER is measured for both wavelengths and compared in Fig. 6a with the theoretical BER for 8dB extinction ratio at 500Mbps. The eye diagrams obtained for 1550nm and 1520nm are shown in Fig. 6b and 6c respectively. Similar BER performance and clear eye opening for both operating wavelengths are observed.

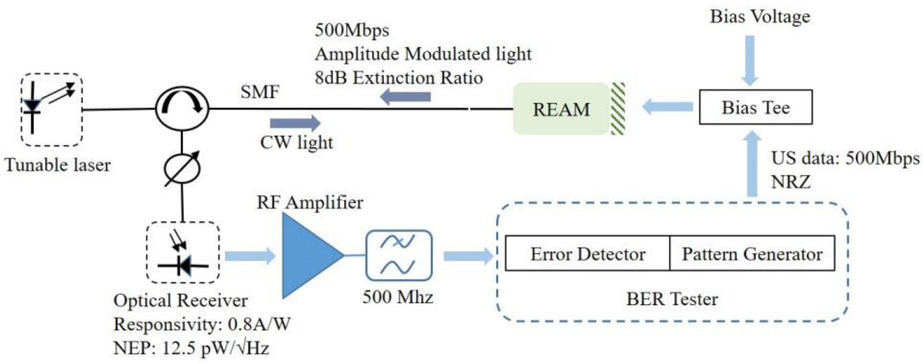

Figure 5 Experimental setup for emulating US link using 500Mbps NRZ data

By driving the REAM at 0.8Vpp using 1520nm light approximately 47% dynamic energy consumption reduction was achieved with similar link performance. The link budget in Table 2 confirms that sufficient link margin is available even with the increased insertion loss at 1520nm.

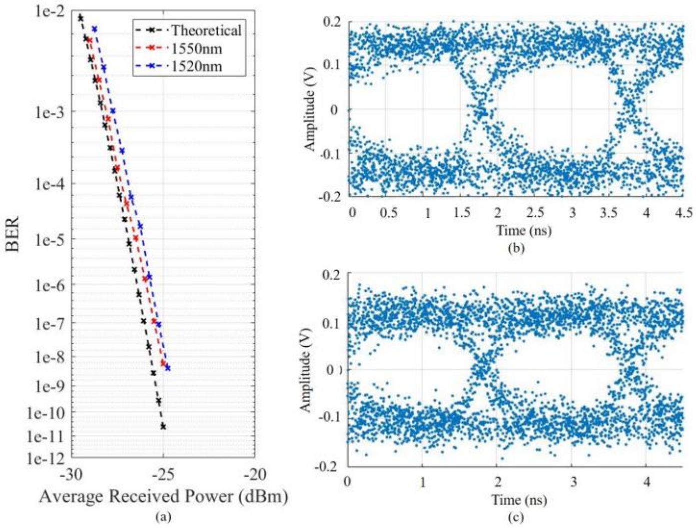

Figure 6 (a) BER performance of US link (500 Mb/s) for 1520nm and 1550nm using REAM as a modulator (8dB Extinction Ratio) and a commercially available optical receiver with Responsivity: 0.8A/W and NEP: 12.5pW/√Hz. (b) Eye diagram of received US signal for 1550nm at -24 dBm received optical power. (c) Eye diagram of received US signal for 1520nm at -24 dBm received optical power

Table 2 Link budget for the Upstream Link

Parameter	Value	Units	Remarks
Laser output	0.0	dBm	
Distance	2.0	m	
Fiber loss	0.2	dB/km	
Total Fiber loss	0.0	dB	
Connectors			
Total number	3.0		
Loss per connector	0.2	dB	
Total Connector loss	0.6	dB	
Circulator			
Loss from laser to REAM port	0.7	dB	
Loss from REAM to Photodiode port	0.7	dB	
Total Loss in circulator	1.4	dB	
REAM insertion loss	12.0	dB	λ = 1520nm, Vpp = 0.8V, Vbias = 0V
Total Component loss	14.0	dB	
Receiver sensitivity	-26.8	dBm	For 500Mbps, 10^{-9} BER and infinite extinction ratio
Power penalty			
Penalty for extinction ratio	1.4	dB	Penalty for 8dB extinction ratio
Link Margin	11.4	dB	

3.3 DS link demonstration using zero-bias REAM

The same US setup with some modification in the electrical connectivity and the addition of a Mach Zehnder Modulator (MZM) shown in Fig. 7 was used to operate the REAM as a zero-biased photodetector to detect 1520nm amplitude modulated light at 500Mb/s with greater than 10dB extinction ratio.

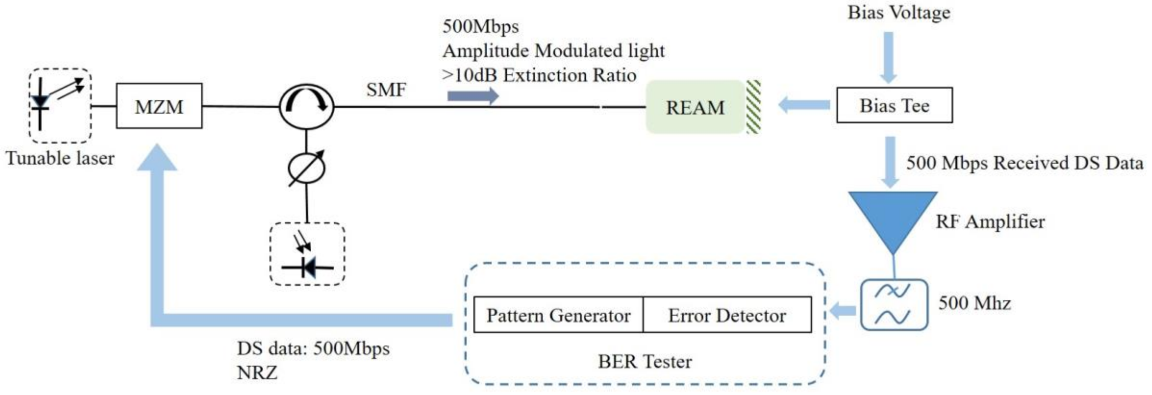

Figure 7 Experimental setup for emulating the DS link for 500Mb/s. The REAM is operating in the receive mode at 1520nm using zero-bias voltage. The photocurrent was amplified using a commercially available RF amplifier and the BER performance was measured using a BER tester. The REAM based optical receiver does not incorporate a transimpedance amplifier as in commercially available optical receivers.

The results in Fig. 8 shows that error free operation (BER < 10^{-9}) was obtained at -7.5dBm received power with a very clear and wide eye opening. In conventional links where the photodetector is expected to detect very low optical intensity owing to the high optical link loss, the receiver circuits incorporate a Transimpedance Amplifier (TIA) and sometimes also, Forward Error Correction (FEC) to improve the receiver sensitivity and correct errors in the received signal respectively. Here, we have demonstrated that error free operation is possible for such an ultra-short link of a few meters without a TIA and FEC in the receiver circuit. This is potentially beneficial in the context of the guidewire application as it eliminates the need for further power and space consuming components from the distal end of the system.

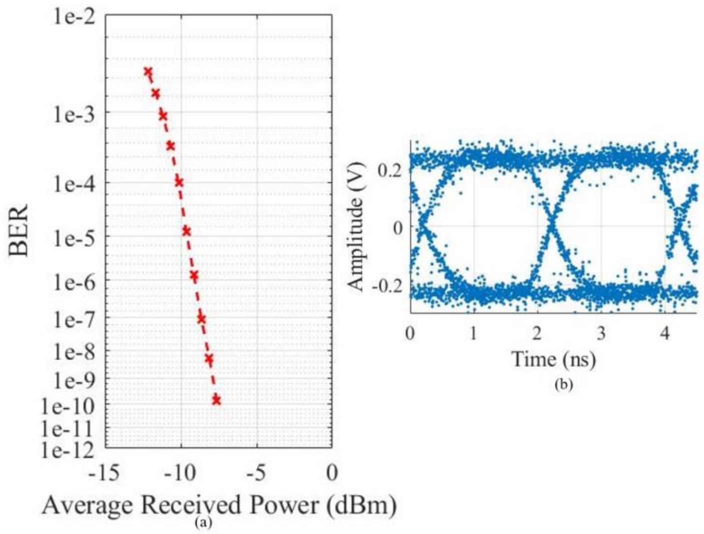

Figure 8 (a) BER performance of the DS link (500 Mb/s) using REAM as the optical receiver operating at 1520nm. Error free operation was observed at -7dBm. (b) Obtained eye diagram at -7dBm for REAM based optical receiver operating at 1520nm.

4. CONCLUSION

In this paper we have proposed and demonstrated a novel optical communication link designed to support real-time imaging for surgical guidewire applications. The proposed link which is based on a TDD communication protocol and the dual functional capability of an REAM removes the need for a power-hungry laser from the distal tip and does not require bulky splitters to separate the DS and US channels. This makes the scheme extremely power and footprint efficient. In addition, we have shown that operating the REAM at wavelengths near the MQW band-edge (1520nm instead of the conventional optimum operating wavelength of 1550nm) reduces the required modulation voltage swing and enables zero-bias operation. This results in negligible static energy consumption and ~47% reduction in dynamic energy consumption of the REAM. Experimental results show that error free operation (BER < 10^{-9}) is possible for such an ultra-short link of a few meters at data rate as high as 500 Mb/s without using a TIA and FEC in the receiver circuit at the distal end, which further reduces the footprint and power consumption of the receiver front end circuit.

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