ABSTRACT OF THE DISSERTATION

Design and Optimization of Bidirectional and Optical Logic Systems in the Presence of Noise

by

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Doctor of Philosophy in Electrical Engineering (Photonics)

University of California, San Diego, 2007

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The work in this thesis covers the critical aspects of optical noise in bidirectional and optical logic systems. With applications ranging from ultra-dense transmission and fiber-to-the-home to all-optically routed networks and optical computing, bidirectional fiber optic links and optical digital logic play an important role in future photonics systems. As with any communication systems, the fundamental performance of bidirectional and optical logic systems is ultimately limited by noise. In this thesis, the impact of optical noise in bidirectional and optical logic systems is investigated with the goal of determining the optimal design and performance requirements of future systems.

Two types of bidirectional optical systems are analyzed: interleaved bidirectional systems and passive optical networks. It is demonstrated, both theoretically and experimentally, that Rayleigh backscattering noise is a fundamental limitation in bidirectional systems. Owing to its absence in conventional unidirectional systems, Rayleigh backscattering noise is an oft neglected noise mechanism in optical fiber systems and few design rules exist which seek to minimize its impact. It is shown that in bidirectional fiber systems, Rayleigh backscattering places markedly unique constraints on optical link design with respect to receiver design, system power budget, capacity and choice of modulation format. New design rules are offered which rigorously account for the deleterious impact of Rayleigh backscattering noise in fiber optic systems.

This thesis also addresses the role of noise in future optical logic systems. In particular, experimental work characterizes the progress of optical Boolean logic functionality in bistable 1550 nm Vertical Cavity Surface Emitting Lasers. Record bistable switching powers in 1550 nm Vertical Cavity Semiconductor Optical Amplifiers are observed and a novel, cascadable 1550 nm optical inverter is demonstrated up to 2.5 Gb/s. Positive noise margins and signal regeneration is achieved representing an important step towards the realization of robust, noise immune optical information processing systems.

1. Introduction

1.1 Information and Noise in Communication Systems

The genesis of the Information Age is marked by the 1948 publishing of Claude E. Shannon's seminal work "A Mathematical Theory of Communication" [1]. In his paper, Shannon described many of the fundamental concepts and principles that would later become the theoretical foundation for the burgeoning scientific field of information theory. One of the central contributions of Shannon's work was, with the aid of previous work by Hartley [2], the simple mathematical relationship linking the achievable channel capacity of a band limited power-constrained signal corrupted by Gaussian noise

$$C = B\log_2\left(1+\frac{S}{N}\right) \tag{1.1}$$

where C is channel capacity (bits/sec), B is channel bandwidth (Hz), S is signal power (W) and N is noise total noise power (W). Physically, (1.1) reveals that the total amount of *error-free* information that can be sent through a noisy channel is limited by the available bandwidth of the channel and the signal to noise ratio (S/N or SNR) of the transmitted signal. Whereas his contemporaries had assumed that no information could be transmitted for sufficiently high noise levels [3], Shannon realized that information buried deep within noise can always be reliably recovered at the expense of lower transmission rates.

This eternal tradeoff between information throughput and channel noise is experienced on a daily basis in modern life. Whether it is the static hiss heard on a terrestrial radio station or the slower than normal loading time of a webpage during peak hours, capacity/noise tradeoffs ultimately determine the quality and speed of data transmission. In many ways, the fields of information theory and communications theory are simply extensions of Shannon's original work which explained that noise, in its various manifestations, is the enemy.[1] *The central task of the communications engineer, therefore, is to understand how best to cope with the noise so as to maximize the amount of information which can be transmitted through a given physical channel (e.g. wireless, copper, fiber optic, etc…)*.

1.2 Optical Communications: Exponential Demand and Fiber Exhaust

From an end-user perspective, the successful elimination of noise in a transmission channel translates to higher connectivity over longer distances and/or larger amounts of deliverable content. In both military and civilian applications, demand for greater interconnectivity coupled with increased bandwidth and processing power is the central driving force behind communications research. This fact is exemplified by the progression of the fiber optics industry over the past 20 years. Although the timing of optical infrastructure upgrades has been difficult to predict historically, as evidenced by the telecommunications market fallout circa 2001,

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[1] Interestingly, Kosko notes that noise in its various forms can actually be beneficial in a variety of applications including image recognition, animal predation and neurocomputing [4].

demand for increased fiber throughput is at an all time high and is growing exponentially [4-6]. Considering the capitol expenditure necessary to deploy new optical networks, it is critically important that next generation optical networking solutions provide economic feasibility in addition to enhanced capacity.

The exponential demand on the fiber optic infrastructure has led to the inevitable consequence of *fiber exhaust* [7]. Fiber exhaust, or perhaps more apply termed “topology exhaust” or “hardware exhaust”, results when a single fiber can no longer supply more data throughput. In effect, the fiber is operated at its *current* capacity limit. Curiously, this capacity limit is not fundamental in the sense that it is not governed by Shannon’s limit. In fact, even the most sophisticated optical systems installed today do not come close to approaching Shannon’s limit. Capacity limitations leading to fiber exhaust are instead the result of technical and economic compromises that are made during system installation. Several years ago, a common solution to fiber exhaust would be to add capacity by lighting previously unused fiber (called “dark” fiber) already in the ground. Unfortunately, the lighting of dark fiber will inevitably become an increasingly rare option due to diminishing supply, especially in high traffic (i.e. urban/metropolitan) areas where the majority of available fibers are already in use. Owing to the considerable installation cost of deploying new fiber, it seems logical, therefore, that alternative solutions must be sought which utilize existing infrastructure in the most efficient way possible.

1.3 Bidirectional Networks and Optical Digital Signal Processing

In this thesis, novel solutions for improving network efficiency and utilization will be explored with the specific goal of analyzing and eliminating the underlying noise processes which limit system performance. Attention will first be paid to the role Rayleigh backscattering (RB) noise plays in bidirectional optical networks. Optimal design of bidirectional links will be discussed with an emphasis on the various techniques available to mitigate RB penalties. The latter portion of this thesis will discuss current developments in all-optical logic based on 1550 nm vertical cavity surface emitting lasers (VCSEL) and Vertical Cavity Semiconductor Optical Amplifiers (VCSOA). With applications stretching far beyond just fiber optic communications, all-optical logic is a coveted functionality in all optical systems for its perceived economic and speed advantages. The impact of optical noise will be addressed in the design of the first fully cascadable VCSEL inverter at 1550 nm.

1.3.1 Unidirectional vs. Bidirectional Systems

Currently, the majority of installed fiber optic systems are unidirectional in the sense that information only travels in one direction down the fiber. A major advantage of this type of system is that signal impairments caused by back-reflected light (be it from discrete or distributed reflectors) can be eliminated with the appropriate use of optical isolators (typically installed at amplification sites as shown in Fig. 1.1). A benefit of the use of isolators at amplification stages is that amplifier self-oscillation can be eliminated thereby allowing larger per stage gain [8]. Because back-reflected

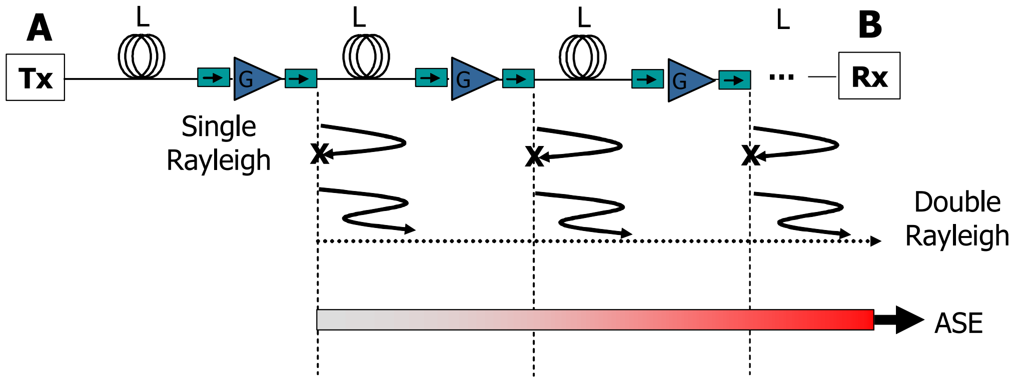

Fig. 1.1. Common unidirectional topology with lumped amplification. Amplification stages occur approximately every 50-100 km to offset propagation loss (typ. 0.2-0.3 dB/km). Amplification nodes are often coupled with additional functionalities like dispersion management and traffic switching. Implementation of optical isolators dramatically reduces RB effects. Double RB (DRB) occurs within the fiber span but is negligibly small compared to ASE growth in the absence of distributed amplification.

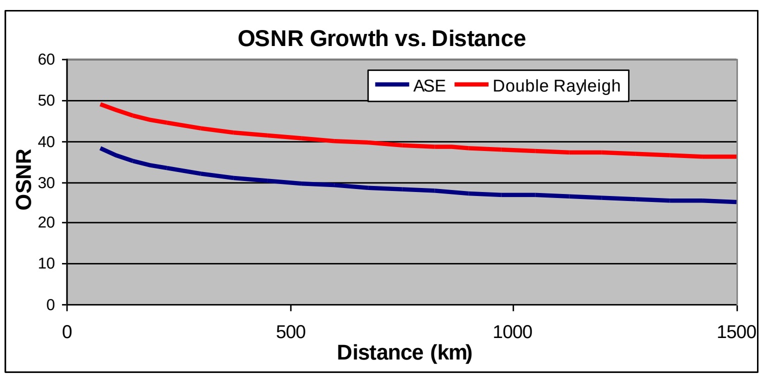

Fig. 1.2. Growth of ASE and DRB in the unidirectional system in Fig. 1.1. ASE limits performance but can be maintained below significant levels for thousands of km with proper link design. Values assumed in the calculation: L = 75 km, fiber loss = 0.2 dB/km, G = 15 dB, amplifier noise figure (NF) = 5 dB, launched power = 1 mW (0 dBm), Rayleigh scattering coefficient per/span = -32 dB.

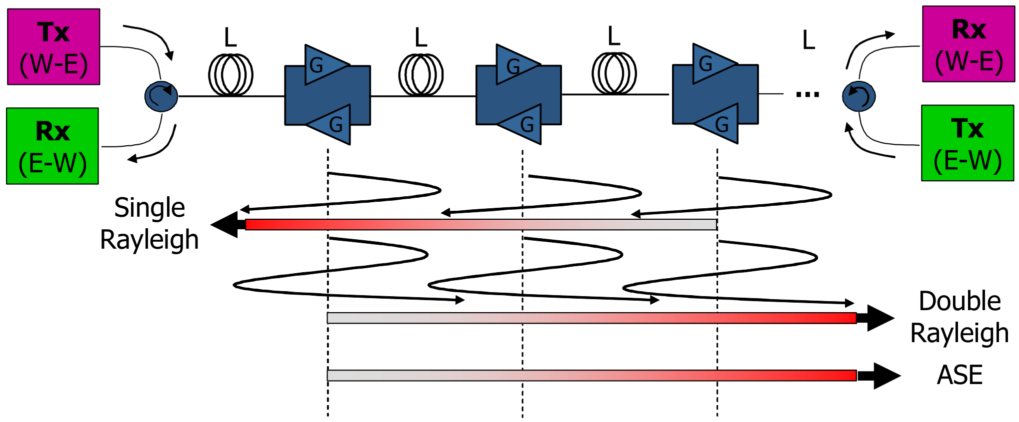

Fig. 1.3. Example of a bidirectional fiber link with both east-west (E-W) and west-east (W-E) communication. Isolators not feasible since information travels in both directions on the same wavelength.

light is negligibly small, unidirectional systems are primarily limited by amplified spontaneous emission (ASE) and nonlinear effects during transport. A simple calculation of the growth of ASE noise in a unidirectional link reveals that error-free transmission is possible over many thousands of kilometers; assuming nonlinear and dispersion impairments are properly dealt with (see Fig. 1.2). A drawback of unidirectional systems, however, is that full duplex communication must occur using a separate fiber cable or separate wavelength band (on the same fiber). From the perspective of hardware efficiency, latency, network integrity and network management, it can be argued that bidirectional communication over a single fiber and wavelength is preferred. With bidirectional signaling, the total aggregate data throughput over a single fiber can be doubled because downstream and upstream traffic can occur at the *same wavelength*.

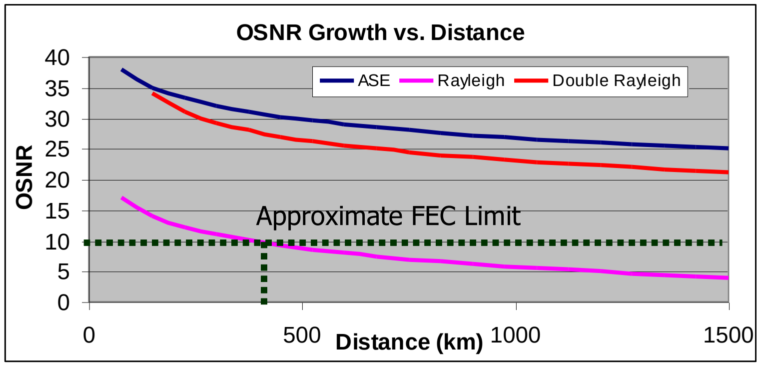

Fig. 1.4. Calculation of ASE, RB and DRB in example link from Fig. 1.3. RB noise severely limits performance when counter-propagating channels use the same wavelength.

Unfortunately, capacity doubling via bidirectional signaling comes with the tradeoff that back-reflected light cannot be removed with inline isolators as shown in Fig. 1.3. Thus, bidirectional networks suffer from additional penalties associated with discrete back-reflections off connector facets and Rayleigh backscattering from fiber inhomogeneity. Although facet reflections can be sufficiently reduced using appropriately designed connectors [9], RB remains a fundamental noise impairment in bidirectional systems as shown in Fig. 1.4. If no countermeasures are taken to limit the effect of RB noise, bidirectional networks are limited to approximately 400 km in systems employing forward error correction (FEC). In non-error-corrected systems where the optical signal to noise ratio (OSNR) must exceed about 15 dB, transmission distance is limited to less than 100 km. It will be demonstrated in this thesis that RB noise in bidirectional networks can be sufficiently suppressed through techniques like frequency offsetting and optimal receiver filtering. With these techniques, the achievable distance of bidirectional systems can be improved by more than an order of magnitude while still maintaining capacity doubling with respect to unidirectional systems.

1.3.1.1 Interleaved Bidirectional Networks

A novel approach to alleviating the 400 km distance limit imposed by single wavelength bidirectional fiber communication is to employ interleaved bidirectional (IB) signaling [10] as shown in Fig 1.5. Several technical advantages are gained by interleaving counter-propagating channels (i.e. W-E signals transmit on odd wavelengths, E-W channels transmit on even channels). The most obvious advantage is that crosstalk penalties due to RB in the transmission fiber are reduced since the signal and RB crosstalk are separated in wavelength. Therefore, proper optical and electrical filtering can eliminate the majority of the crosstalk. Another advantage of IB signaling is that nonlinear effects like cross-phase modulation (XPM) and four photon mixing (FPM) can be mitigated because phase matching conditions are violated for larger frequency separation between co-propagating channels [11]. This point is important because of recent trends towards high spectrally efficiency (SE) optical systems. These so-called ultra-dense wavelength division multiplexing (UDWDM) systems attempt to pack channels as tightly as possible causing greater interchannel nonlinear and coherent crosstalk [12, 13]. By relaxing the co-propagating channel spacing, IB signaling may offer an alternative solution to UDWDM while still maintaining the same amount of aggregate throughput in the fiber. The final benefit of IB signaling is that network assets (specifically amplifiers) can be used more efficiently [14]. Since the most commonly deployed optical amplifiers, erbium doped

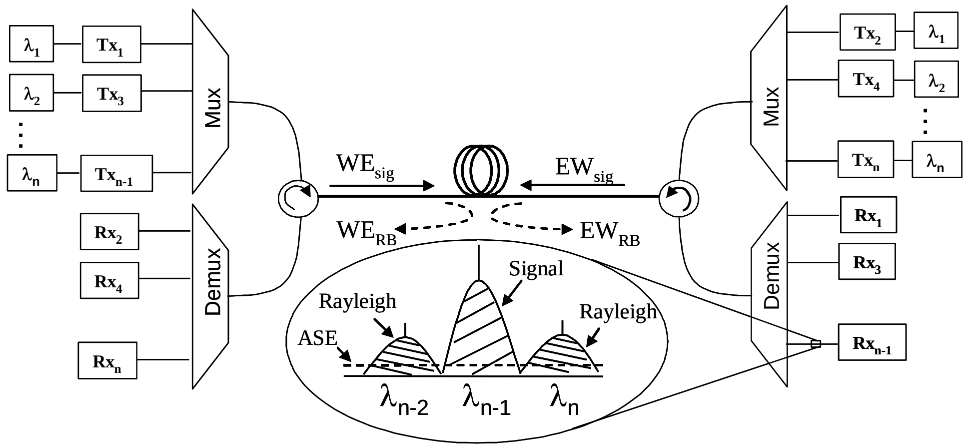

Fig. 1.5. Interleaved Bidirectional System. Duplex communication is possible by transmitting unidirectionally on alternating channel. RB crosstalk from adjacent channels is mitigated by filtering in the demultiplexer (demux).

fiber amplifiers (EDFA) and Raman amplifiers (RA), are inherently bidirectional, IB signaling offers an optimal method for maximizing capacity within a transmission band without the need for a doubling of equipment. This advantage contrasts with *banded* bidirectional signaling which would need dedicated amplifiers to amplify counter-propagating signals in the C and L bands, for example.

While the impact of coherent (intrachannel) RB noise is a well explored topic on account of past studies of DRB (also called multi-path interference (MPI)) effects RAs [15], there is currently a limited understanding of the impact of incoherent (interchannel) RB noise in IB-UDWDM systems, particularly regarding the appropriate modeling and optimization of such systems. In this thesis, issues regarding the ultimate SE achievable using IB signaling will be elucidated with particular focus on the suppression of RB impairments. New system design paradigms

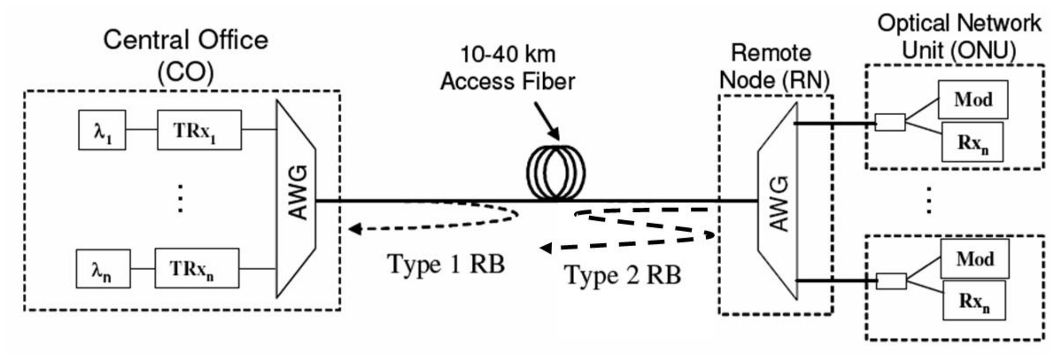

Fig. 1.6. CLS-PON Topology. Placing the light source at the CO allows for flexible wavelength allocation to the customers. The ONU must only provide modulation and detection. RB limits systems margin and devices caused by both the downstream (Type 1) and upstream (Type 2) launched light.

for IB links will be proposed and clear distinctions will be made between the optimal design of RB limited versus ASE limited fiber optic links.

1.3.1.2 Passive Optical Networks

Passive optical networks (PON) have garnered interest in recent years from network providers and researchers alike owing to their tremendous economic advantages for applications in "last mile" services and optical sensing [16]. In fact, at the Optical Fiber Communcations Conference (OFC) 2007 the keynote address by Verizon Senior Vice-President Mark Wegleitner discussed the most recent progress in the deployment of gigabit-capable PONs for fiber to the premises (FTTP) applications [6]. Current forecasts predict over 18 million more homes to be installed with fiber access by 2011.

PONs are a type of bidirectional network which seeks to provide full duplex communication between a service provider central office (CO) and various customer optical network units (ONU) as shown in Fig. 1.6. The key requirements of PONs are that the installation and upkeep of the network remain minimal while also maintaining minimal hardware cost. In order to meet these economic and technical constraints, the existing fiber infrastructure must be used as efficiently as possible. Hence, communication between the CO and multiple ONUs occurs over a single fiber as shown in Fig. 1.6. Additionally, many of the expensive techniques afforded in more expensive network topologies (advanced modulation formats, dispersion compensation, etc…) are unfeasible in PONs thus requiring engineers to provide cost effective solutions for the myriad technical constraints.

Since PONs provide bidirectional signaling over a single fiber, system margin is often dominated by RB noise [17]. In this thesis, the reduction of RB penalties in PON-type applications is discussed with particular focus on PON architectures utilizing centralized light sources (CLS) [17, 18]. Owing to its cost efficient design, the CLS-PON is particularly well suited for FTTP applications in next generation PONs. Techniques for RB reduction in PON-CLS networks will be presented and a new model for noise performance will be detailed.

1.3.2 All-Optical Systems

A long coveted functionality of photonic systems is the ability to provide optical digital signal processing (DSP) on optical data streams. With applications in optimal memory, optical routing and optical computing, optical DSP it is expected to be a key component in future optical communication systems. Currently, required networking functionalities like signal routing and data buffering must be completed in the electrical domain. This electrical solution, although effective, is a hindrance in terms of network latency, bandwidth and power consumption because of the requirement for optical-electrical-optical (OEO) signal conversion. It is widely believed that future optical networks will replace these costly OEO nodes with photonic technologies with ODSP capability.

Although various techniques exist which can optical DSP, no clear technology platform has emerged due to various shortcomings in terms of cascadabilty, speed, power, size, large scale integrability and cost of logic elements. Recently, VCSOAs have receiver considerable attention for such applications on account of their small size, high nonlinearity and large scale 2D integration capability. Unfortunately, most efforts have focused on applications in the 850 nm wavelength band. To date, VCSOA work in the important 1550 nm telecom band is still nascent as a result of the greater difficulty in fabricating 1550 nm VCSELs. Of primary importance in the development of 1550 nm VCSOA technology is the observation of cascadable optical logic operation. In DSP, the successful cascading of many logic elements (i.e. Boolean gates) is predicated on the individual gates' ability to regenerate the logic levels in the presence of noise. The integrity of the digital system to the presence of noise is called its *noise immunity* and is dependent on the to the nonlinear input-output transfer characteristic (TC) of the individual gates and there ability to perform logic level regeneration [19, 20]. In this thesis, recent work in the area of 1550 nm VCSOA logic will be discussed and a cascadable inverter with adequate noise margins and logic regeneration will be demonstrated up to 2.5 Gb/s.

1.4 Thesis Outline and Contributions

The contributed work of this thesis comprises four main chapters. Chapters 2 and 3 are primarily concerned with the modeling and optimization of links corrupted by coherent and incoherent RB noise. Chapter 2 begins with the methodology used to characterize RB noise in fiber systems. Two distinct models will be described: an analytic model using Gaussian approximations for the filter and pulse shapes and a numerical model which accounts for exact modulation spectra and inter-symbol interference (ISI) effects caused by filtering. The models are then compared to experimental results. The modulation formats non-return to zero (NRZ), return to zero (RZ) and Duobinary (DB) are compared experimentally and it is found that spectrally narrow modulation formats can achieve the highest possible spectral density assuming *format tailored filtering* is implemented. Additionally, it is determined that incoherent RB noise is best modeled using numerical techniques which can account for exact power spectral densities and filter induced ISI.

Based on the conclusions from Chapter 2, Chapter 3 uses the numerical model to determine the optimal receiver design for optical links degraded by both coherent and incoherent RB. It is found that the design of the receiver's optical and electrical filters plays a key role in the error-free detection of signal in the presence of unwanted RB noise. This conclusion is especially true in IB networks where the receiver filters tend to optimize for unconventionally narrow bandwidths. Design rules are proposed for several common modulation formats in the presence of coherent and incoherent RB noise.

Chapter 4 describes the role that DC block filtering can play on the suppression of RB noise and discrete interferometric crosstalk (IC). Heretofore overlooked in the literature, DC blocking proves to be an inexpensive yet powerful means of linear crosstalk mitigation, particularly in PON-CLS topologies. Experimental results agree with theoretical insights and show that optimal low-frequency cutoffs (LFC) in the receiver bandwidth tend to be significantly larger in RB degraded and IC degraded links. These results are then placed within the context of the CLS-PON. A generalized CLS-PON noise model is developed. It is determined that DC blocking used in conjunction with receiver low pass filtering can result in span length increases up to 53% longer than those previously calculated in the literature.

Chapter 5 details the design of a cascadable 1550 nm VCSOA inverter utilizing cross gain modulation (XGM), dispersive bistabilty and polarization injection locking. The chapter begins with the experimental observation of all three forms of reflection mode bistabilty (i.e. clockwise, counterclockwise and butterfly) in 1550 nm VCSOAs. The reported results represent the first ever observation of butterfly bistabilty in VCSOAs. Also, counterclockwise bistabilty is found to occur at a record low switching power of 2 μW. The latter part of the chapter discusses the design of the first ever cascadable 1550 nm VCSEL inverter. Necessary conditions for cascadable operation are described and it is found that inverters with sufficient noise characteristics are possible up to data rates of 2.5 Gb/s.

Chapter 6 provides a summary of the contributions made in this thesis along with a review of some relevant technical questions yet to be answered.

Appendix I provides a summary of the important statistical considerations necessary for the treatment of RB noise. Based on physical arguments, it is shown that under the most typical operating conditions, RB can be quantified as being a complex circular Gaussian (ccg), wide sense stationary (WSS) random process whose spectral density is given by the original launched light.

Appendix II gives a review of the modulation formats studied in this thesis. The most common transmitter architectures used to create the various formats are described and typical eye diagrams and spectral characteristics are illustrated.

Finally, Appendix III details the rigorous approach needed to accurately compare the theoretical and experimental results in Chapter 2.

1.5 References

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