6. Conclusion

This thesis has been concerned with the impact of non-traditional noise mechanisms in optical systems. In the Chapters 2 through 4, efforts were made to quantify and mitigate the deleterious impact of optical noise caused by distributed Rayleigh backscattering in bidirectional fiber optic systems. Owing to their intrinsic capacity doubling, efficient infrastructure use and enhanced nonlinear immunity, it is clear that bidirectional signaling systems offer novel solutions to many impending problems in future optical networks. Whether it is incoherent RB in IB links or coherent crosstalk in PONs, it has been shown throughout this thesis that linear optical crosstalk merits special consideration when designing future optical systems.

In a similar fashion, Chapter 5 examined the role of optical noise in the mostly unexplored field of digital OSP. Although the underlying details and applications may be starkly different from those of bidirectional systems, digital OSP, and the underlying design of such systems, requires careful noise analysis when designing robust systems. By borrowing principles from the well established field of (electrical) DSP, it has been demonstrated that current 1550 nm VCSEL technology may offer potential for OIP in future systems. The nonlinear reshaping functionality of the VCSEL logic elements allows for inverter concatenation due to positive noise margins and ER regeneration. These findings represent a first critical step towards the ultimate goal of highly integrated OIP technology.

As with any scientific contribution, this work has motivated many new questions and directions. In the coming sections, the overall contributions will be summarized and suggestions will be offered for future work.

6.1 Bidirectional Systems

6.1.1 Contributions

Based on the conclusions of Chapters 2 through 4, it is clear that RB plays a key role in the optimization of bidirectional systems. While the contemporary approach has been to approximate RB noise spectra [1, 2], the conclusions of this thesis have definitively shown that exact performance predictions in the presence of RB must include exact spectral characteristics. While the approximations offer experimental and/or mathematical convenience, the rigorous treatment of RB elucidates a deeper, more profound impact. For the case of dense IB links, it has been shown repeatedly that a specific modulation format has its own unique performance in the presence of RB and that receiver filter design can vary drastically when compared with traditional design rules. In general, incoherent RB limited links warrant narrower-than-normal filtering in order to optimize sensitivity. However, under the special case of DB modulation, careful ISI analysis reveals that DB signaling is RB noise *invariant* because of the enhanced ISI immunity. Of the modulation formats studied, DB tends to achieve the most spectrally efficient IB link topologies.

Unfortunately, there exist many examples where coherent RB limits performance rendering the design protocols presented in Chapter 2 and 3 inaccurate. In these cases, conventional mitigation approaches have sought to broaden the signal and/or noise field in order to generate higher frequency beat noise [3-6]. Both costly and inefficient from a system design perspective, spectral broadening remains impractical in most situations, especially for applications in PONs where additional dBs of power margin are a precious commodity. By contrast, it has been demonstrated that proper AC coupling at the receiver significantly reduces coherent RB due to the disproportionate amount of low frequency beat noise generated during photodetection. This method proves to be robust and inexpensive and is especially applicable in CLS-PON links corrupts by Type 1 and Type 2 RB noise. It was further demonstrated using a generalized CLS-PON noise model that the low pass and high pass frequency response of the receiver electronics has a critical impact on achievable reach. If the rigorous frequency characteristics of the system are not carefully considered, errors in predicted reach can exceed 53%.

6.1.2 Suggestions and Future Directions

This work was concerned with characterizing the impact of RB noise in terms of back-to-back performance so as to determine baseline limitations. In practice, performance of the system will depend on the propagation characteristics of the entire link. Central to the development of robust bidirectional systems will be the question of how best to allocate amplifier technology in the link. Several interesting questions arise. What is the optimal amplification strategy for IB links? What role will distributed Raman amplification play? Can power budget asymmetry improve SNR through the use of unidirectional amplifiers? Moreover, how does the presence of counter-propagating channels change the amplifier design itself? Based on the results of Chapter 4 regarding CLS-PON, it is clear that factors such as span loss and amplifier gain play an enormous role in the accumulation of RB in bidirectional systems indicating that the key to RB mitigation involves the prudent design of the link power budget. Just as was done in Chapter 2, analysis must be conducted which determines the impact of amplification schemes (both amplifier type and power map) on both the amplification of RB and the introduction of additive ASE. If such theoretical and experimental work is successful, it is conceivable that long haul bidirectional systems can become commonplace for a variety of applications.

6.2 VCSEL-based OIP

6.2.1 Contributions

The bistability and inverter studies described in Chapter 5 represent important contributions to the field of VCSEL-based optical logic. The ability to provide μW switching in a bistable 1550 nm VCSOA indicates that VCSEL technology may offer a good compromise between size, power and potential for large scale integration for OIP applications. Although the devices measured did not possess sufficient gain to achieve cascadable logic below the lasing threshold, it was demonstrated that above threshold operation may be a viable alternative. In addition to the enhanced gain above threshold, it was determined that the speed of a cascadable VCSEL inverter could reach 2.5 Gb/s. The errorless operation at 2.5 Gb/s using a VCSEL-based inverter is the first ever demonstration of its kind. The positive noise margins and regenerative aspects of the inverter provide the necessary and sufficient conditions to achieve cascadable operation of multiple gates. Above all, it has been demonstrated that the low powers and highly nonlinear responses of the VCSELs provide a suitable platform for the ultimate goal of highly integrated all optical DSP at 1550 nm.

6.2.2 Suggestions and Future Directions

The future of VCSEL based logic will likely be determined based on advancements in two general areas: the improvement and optimization of the devices and the development of a robust, system level OSP model. First, the VCSELs used in this work were commercially available devices designed for 2.5 Gb/s direct modulation applications. It is probable that these VCSELs have sub-optimal properties for optical logic applications. These particular devices were presumably designed to act as directly modulated lasers such that the mirror reflectivities and gain layers promote optimally low threshold current and high speed modulation characteristics. It has been predicted in multiple studies that the optimal VCSOA structure may differ greatly from the optimal VCSEL structure [7, 8]. Therefore, future work should be dedicated to re-designing the VCSOA structure in detail. With application-specific device optimization, the switching powers and I/O characteristics of the logic gates may be improved tremendously.

Second, a better understanding of the system level aspects of OSP is required. In particular, it will be necessary to understand how many hundreds, thousands, and even millions of optical gates will behave on a system level. This directly relates to the concept of noise immunity mentioned in Chapter 5. In principle, any digital logic circuit must be able to operate without error as signals are passed from gate to gate. Interestingly, the issue of noise accumulation and operation stability has received little attention for OSP applications, in part due to the experimental difficulty of even demonstrating single gate functionality. Nonetheless, it would be illuminating to explain the operation of a many-gate optical logic system from a higher level perspective, both because it may offer insight into how individual devices should be designed and fabricated and because it may reveal additional challenges which would not otherwise understood using a bottom-up approach.

6.3 References

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