Optical Amplifier Options for Wideband Submarine Systems

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Abstract *The main wideband amplifier candidates for use in submarine systems are hybrid DRA/EDFA and C+L band EDFAs. We explore the relative merits of the two technologies and demonstrate through simulations that the hybrid approach is advantageous for most systems.*

Introduction

Submarine systems have enjoyed the tremendous advances in coherent transmission brought about by high speed DSP technology over the last few years. These techniques have brought us remarkably close to the Shannon limit. Increasing the transmission capacity further is achievable by selecting improved system parameters such as a smaller fibre attenuation coefficient and a lower nonlinear coefficient. However, these improvements only yield logarithmic increases in channel capacity. For linear increases in capacity the three main options are multi-core transmission, multi-mode transmission or increased bandwidth. In this paper we explore the latter, which is, perhaps, the most pragmatic option. Current repeater amplifier bandwidths are typically 35nm and here we explore the relative merits of the two most viable options to double this bandwidth to 70nm, namely hybrid Distributed Raman/EDFAs (DRA/EDFAs) and C+L band EDFAs.

Amplifier topologies

The basic structure of the two amplifier types considered are shown in Figs 1 and 2 for a single direction of transmission.

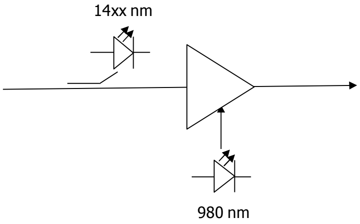

Fig. 1: Hybrid DRA/EDFA structure

Fig. 1 shows the typical hybrid structure in which the EDFA is pumped by a 980nm laser and the DRA is backward pumped by a 14xx laser. The Raman laser wavelength is chosen according to the required wave band, and in this work a wavelength of 1495nm has been chosen. The number of pumps is typically minimised for reliability reasons and so a single Raman wavelength is employed in this study.

The typical structure of a C+L band EDFA is shown in Fig.2. The separate C and L band amplifiers firstly require that the waveband is split by a C/L band splitter at the front end. Also, a 2 stage L-band amplifier is required to enable both a low noise figure and a high output power to be achieved. There are many L-band amplifier configurations possible and here we have chosen simple forward pumped stages with a 1480nm pump for the second stage.

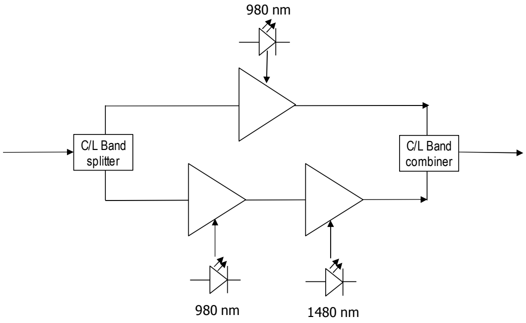

Fig. 2: C+L Band EDFA structure

In both cases, we need to provide 3dB more output power compared with C-band amplifiers if we are to achieve the same channel power over the increased bandwidth.

Hybrid Amplifier Properties

By using a single Raman pump, the on-off gain is necessarily sloped. The dB on-off gain increases in an approximately linear fashion with wavelength until it reaches a peak at 1600nm. This positive slope is complemented by the EDFA design which has a negative gain slope. One of the most unusual properties of the DRA is the variation of noise figure with wavelength. The noise figure decreases as the on-off gain increases. This is illustrated in Fig. 3. Since the DRA comprises the complete span, the noise figure includes the span loss. In the figure, the span loss has been subtracted from the noise figure to produce an effective noise figure, which eases comparison with the EDFA noise figure.

The noise figure of the hybrid amplifier is dominated by the DRA and so, given a flat input spectrum, the system OSNR will also improve with increasing wavelength. One way to exploit this is to use a flex-rate transceiver. At higher wavelengths we can, for example, use higher order modulation formats or a low latency FEC. Alternatively, we can pre-emphasize the channel power to achieve a flat OSNR spectrum at the receiver. This latter approach has been used here as it is more energy efficient.

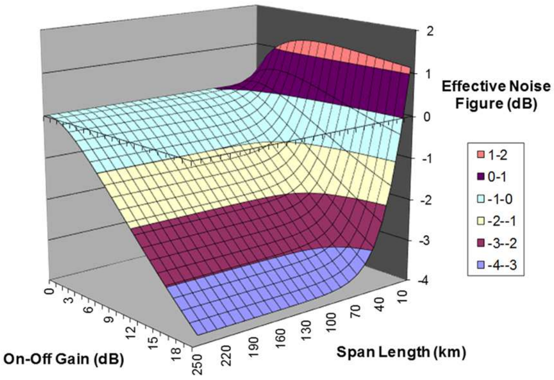

Fig. 3: DRA Noise Figure

C+L Band EDFA properties

The band separating filter at the input to the amplifier typically has a cross-over region of at least 2nm, and so this area of the band cannot be used. However, the bandwidth shortfall can be made up elsewhere. The splitter will have a finite loss and this adds directly to the noise figure of the amplifier. The loss of the band combiner at the output will reduce the output power.

Amplifier Performance

The performance of the amplifier designs has been compared for span lengths ranging from 70km to 150km. The fibre attenuation coefficient was 0.176dB, the effective area 80µm^2 (unless otherwise stated) and the dispersion 17ps/nm-km. Where relevant, the comparison assumes a required OSNR of 13dB in 0.1nm and Nyquist channel spacing. The designs are limited either by available pump powers or nonlinearities.

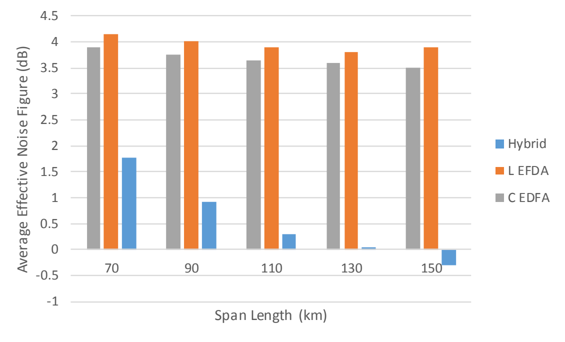

Fig. 4: Noise Figure comparison

In Fig. 4 the average effective noise figure of the designs are shown over the band. While the C and L band noise figures are similar, the hybrid effective noise figure is significantly less, most notably for the longer spans. This immediately demonstrates an advantage of hybrid designs for longer span lengths. However, the output power of the hybrid amplifiers is limited compared with the C+L EDFA design as the 980nm pump has to supply the power for both bands. As a result the channel power of the hybrid designs tends to be lower than for the C+L band EDFA designs for the available pump powers. This is illustrated in Fig.5.

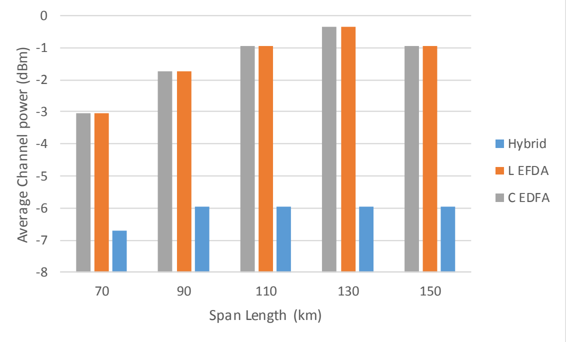

Fig. 5: Channel Power Comparison

Considering the C+L EDFA design first, the maximum channel power is used for 130km spans. Below that span length, the output power is limited by nonlinearities. For span lengths above 130km, the channel power is limited by the available C band 980nm pump power. The low noise figure of the hybrid amplifiers and the high output powers available for the C+L band EDFAs counter each other in OSNR comparisons and appears to put both technologies on a par. However, for span lengths of 130km or less, high effective area fibre must be used to support the higher available powers whereas hybrid amplifiers only need standard 80µm^2 fibre with its associated high pump efficiency. Here, an effective area of 130µm^2 was assumed for C+L EDFA designs up to and including 130km.

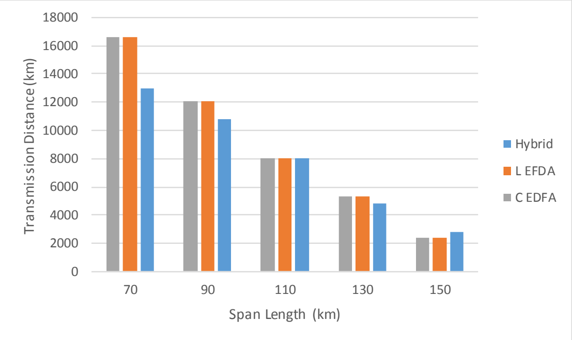

Fig. 6: Transmission Distance

The transmission distance achievable using both amplifier types is shown in Fig. 6. It can be seen that the distances are comparable for most span lengths except for trans-Pacific systems where C+L band amplifiers are preferable.

One interesting consequence of the sloped noise figure is that the standard analytic GN formula[1] cannot be used to estimate the nonlinear performance because of the pre-emphasis. Instead, the GN reference formula[1] must be integrated numerically. This is illustrated in Fig.7. The GNLI noise dips at the band edges, as expected, and it is also sloped. In the example shown, the GNLI noise is 3dB below the ASE noise (i.e., the optimum ratio) at around 1542nm but since the nonlinearity decreases at higher wavelengths due to the pre-emphasis, the GNLI slope is greater than the ASE slope. This also demonstrates that the ideal pre-emphasis should have a larger slope than the ASE slope.

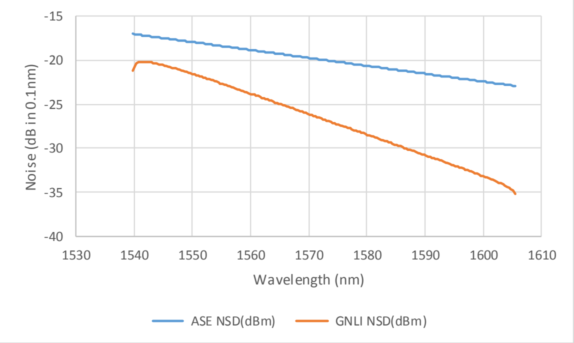

Fig. 7: Nonlinear Noise Slope

The shorter wavelengths in the hybrid design have a higher noise figure and channel power than the average values shown in Figs. 4 and 5. This has been taken into account when calculating the reach in Fig. 6.

The GN model can accommodate the up-tic in channel power towards the end of the span due to the DRA. The additional NLI enhancement factor has been shown to increase with on-off gain but is a relatively small effect[2]. In our case, the on-off gain is relatively small at the lower wavelengths and at higher wavelengths, where the on-off gain is higher, the channel power is low and so there is minimal nonlinear penalty.

Other Considerations

One of the reasons the hybrid designs outperform the C+L band EDFAs at higher span lengths is that DRAs have the property that the dB Raman gain doubles for a 3dB increase in pump power[3] and so pump efficiency increases with span length. For saturated EDFA designs, the output power increases by only ~3dB for a 3dB increase in pump power. In addition, the noise figure tends to improve with longer span lengths as the on-off gain increases. The total electrical power required to power the pumps is illustrated in Fig. 7, assuming 20% and 40% efficiency for 1480nm and 980nm pumps respectively. The C+L band designs are slightly more efficient, and this becomes important over trans-Pacific distances if double-end feeding is to be avoided.

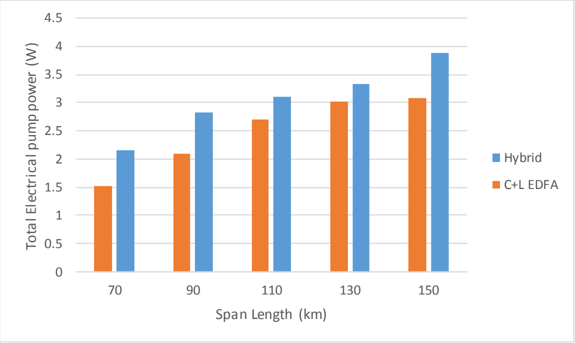

Fig. 7: Total Electrical Pump Power

A useful feature of the Hybrid amplifier designs is that any accumulated spectral slope can be controlled by trimming the DRA pump power. Although this will affect the input power to the EDFA stage, the saturation properties of the EDFA ensure that the output power of the EDFA remains fairly constant. This attribute is very useful in overcoming slope changes due to cable repairs and obviates the necessity of slope equalisers.

Conclusions

Both DRA/EDFA amplifiers and C+L band amplifiers have their place in submarine systems and their relative merits have been explored above. The advantages of hybrid amplifiers are that they have a significantly lower component count and therefore greater reliability, they have a low intrinsic noise figure, they have a continuous transmission band, they only require $80\mu m^2$ fibre, which allows for a less expensive cable, they provide automatic slope control and their bandwidths are potentially extendable to 100nm. By comparison, if the system is power limited, then a C+L band design or a C-band only design is advantageous. In this case, the optimum span loss has been shown elsewhere to be ~9dB[4] and a higher cost has to be accepted to achieve the necessary performance.

References

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