A LOW-ATTENUATION, HIGH SBS-THRESHOLD FIBER LINK OPTIMIZED FOR UNREPEATERED SYSTEM TRANSMISSION AT 10.7 GBIT/S

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Abstract: We combine two fiber types to optimize the SBS-limited performance of a long unrepeatered system with 1550 nm transmission at 10.7 Gbit/s. One fiber is a low-attenuation ITU-T G.654-compliant silica core fiber with typical 1550 nm attenuation about 0.165 dB/km and SBS threshold comparable to standard single-mode fiber. The second fiber type is ITU-T G.652.D-compliant fiber with a high SBS threshold typically at least 3 dB higher than conventional G.652-compliant fiber. We investigate theoretically and experimentally a single long heterogeneous span and demonstrate transmission ≥300 km with NRZ signals and without Raman amplifiers. The ratio of the constituent fiber lengths is optimized to balance the SBS threshold and thus maximum channel launch power with total span loss.

1 INTRODUCTION

Two of the primary limitations of long unrepeatered span submarine transmission systems are fiber attenuation and Stimulated Brillouin Scattering (SBS) nonlinear impairments[1]. The OSNR of the received signal is largely determined by the optical channel power at the end of the span entering the optical pre-amplifier. The received power is of course determined by the span loss through fiber attenuation and the channel launch power level which is often limited by SBS. To achieve long single-span distances, system architects may resort to high launch powers, alternative modulation formats, remotely pumped amplifiers, Raman amplifiers at one or both ends of the span, and strong FEC [2-4]. We investigate here a simple approach to increase the SBS threshold by several dB in a passive way by the appropriate design of a heterogeneous fiber span that combines two different fiber types. Such an increase in SBS threshold corresponds to a reach increase of approximately 25 km, based on a higher allowable launch power per channel. The two fiber types used in our analysis and experiments are Corning® Vascade® EX1000, a low-attenuation silica core ITU-T G.654-compliant fiber with typical 1550 nm attenuation of about 0.165 dB/km[5], and an enhanced SBS-threshold single mode fiber that is compliant with ITU-T G.652.D and has an SBS threshold at least 3 dB higher than conventional standard single-mode fibers[6].

Experimentally, we first measure the SBS threshold of several heterogeneous spans comprised of different lengths of the high SBS-threshold fiber with a fixed long length (>300 km) of the G.654-compliant Vascade EX1000 fiber and compare the results to theoretical and modeling predictions. We find that an increase of SBS threshold of more than 4 dB is possible relative to that of a homogeneous span of the single G.654-compliant fiber alone. This increase translates directly into longer reach because of the ability to transmit higher launch powers in the span. It may also allow the reduction of frequency dithering, which furthers system simplification and minimization of any potential adverse system effects from dithering. Finally, we demonstrate single channel and WDM system transmission over a span of >300 km with NRZ modulation format signals and simple EDFA amplification by taking advantage of the optimized span design. The combination of low overall attenuation with increased SBS-threshold enables significantly longer unrepeatered reach in comparison to spans composed of either constituent fiber alone.

2 EXPERIMENTAL AND MODELED SBS THRESHOLD BEHAVIOR

To begin, we investigated the SBS behavior of a long unrepeatered transmission span comprised primarily of the low-attenuation G.654-compliant fiber with different lengths of the high SBS-threshold G.652-compliant fiber located at the span input. That is, in each case the overall span was made up of a relatively short piece of the high SBS-threshold fiber (fiber1) followed by a long piece of the Vascade EX1000 fiber (fiber2). The SBS characteristics of the spans were evaluated with experimental measurements of the reflected power as a function of channel launch power for a single optical channel. The channel wavelength was 1550 nm and the signal was modulated at 10.7 Gb/s with the NRZ format. No frequency dithering of any kind was applied to the source laser. A conventional set-up was used to measure the reflected Stokes power with a circulator preceding the fiber span and a power meter detecting the reflected light. The measurement results are shown in Figure 1. The length of Vascade EX1000 fiber in the experiments was maintained at 304 km while the length of the high SBS-threshold fiber was varied from 0 to 30 km.

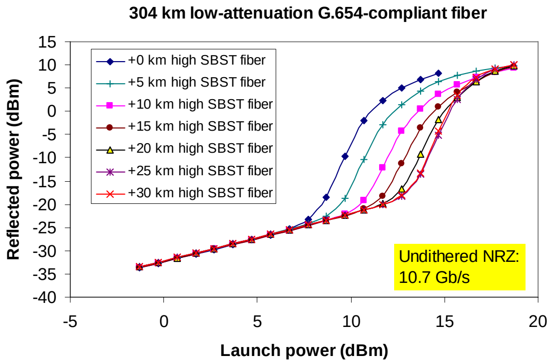

Figure 1: Experimental results for SBS reflected power for a span comprised of varying lengths of high SBS-threshold fiber plus 304 km of low-attenuation G.654-compliant fiber.

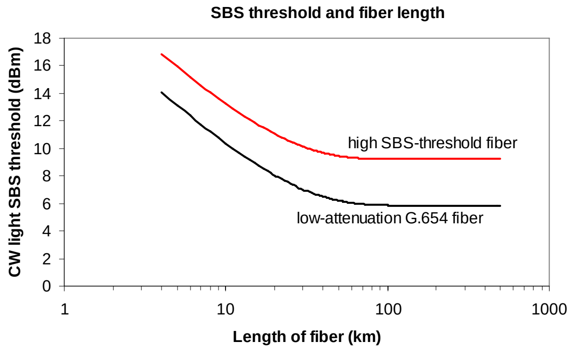

Figure 2: Theoretical model dependence of SBS threshold on length of fiber for two fiber types.

As seen in Figure 1, the experimentally observed SBS threshold increases with increasing lengths of the high SBS-threshold fiber at the span input. This is true at least for small lengths of that fiber in comparison to the fixed long length of the low attenuation G.654-compliant fiber. The threshold in dBm increases nearly linearly with the length of the high SBS-threshold fiber at the span input out to about 20 km. The increase observed in this range is roughly equal to the loss of the short piece of high SBS-threshold fiber. Beyond 20 km, the behavior begins to change, as the SBS threshold obtained with 25 km of the high SBS-threshold fiber1 is only marginally greater than that obtained with the 20 km piece, and the threshold for a 30 km piece of fiber1 is the same as that for 25 km. From these results, it therefore appears that a long unrepeatered transmission span comprised of these two fiber types may be optimized for SBS-limited transmission with approximately 20-25 km of the high SBS-threshold G.652-compliant fiber followed by the much longer length of low-attenuation G.654-compliant fiber.

We can explain this experimentally observed behavior by first noting that it is well-known that the SBS threshold of a fiber span is highly dependent on the length of the fiber, at least for distances on the order of approximately 50 km or less [6,7]. This property is illustrated in Figure 2 which shows the theoretically calculated SBS threshold for CW light for the two fiber types of interest here: the low-attenuation G.654-compliant fiber and the high SBS-threshold G.652-compliant fiber. In particular, the SBS threshold decreases rapidly as fiber length increases for short pieces of fiber <50 km and then becomes essentially independent of length for spans longer than 50 km.

It has been previously demonstrated that heterogeneous combinations of two or more optical fibers with significantly different Brillouin gain spectra like those modeled in Figure 2 can produce a higher overall SBS threshold in short total span lengths such as 20 km [8]. However, for long total span lengths of 100 km or more as are of interest for unrepeatered submarine spans, a slightly different effect can be exploited to produce a higher effective SBS threshold by combining two such fiber types. For a long transmission system, we are interested in using the low-attenuation fiber as the main fiber medium in order to minimize span loss and maximize signal OSNR at the receiver. However, the data in Figure 2 suggests that a short piece of high SBS-threshold fiber placed at the input end of the span can raise the SBS threshold and allow higher powers to be launched. The reasoning is straightforward. Consider a length of the high SBS-threshold fiber on the order of 25 km or less. The SBS threshold of such a short piece of fiber is quite high, approximately 11 dBm for CW light, and higher than that by ~3 dB for a signal with NRZ modulation. Thus the amount of back-reflected Stokes power in this short fiber piece is very small compared to Stokes power generated in the long second piece. That is, when the reflected power begins to appear when launch power increases, it is entirely due to the long fiber piece. And since the Brillouin gain spectra of the two fibers do not overlap in principle, the Stokes power from the long second fiber is not amplified in the first piece. So when the channel power P_{launch} launched into the whole span is high enough to start generating reflected Stokes power in fiber2 it is still less than the SBS threshold of the first fiber piece, and no significant reflected Stokes power will be created in this piece of fiber.

Since the Brillouin gain spectra of the two fiber pieces do not overlap, for channel powers less than its SBS threshold, the short fiber piece merely attenuates the channel power before it reaches the long piece. This means that by the time the launched channel reaches the main transmission fiber (fiber2), it has been reduced in power by the loss of the first fiber piece, L_{fiber1} (dB). Therefore we can expect the amount of measured reflected Stokes power from SBS to be about equal to that generated by a launch power of ($P_{launch} - L_{fiber1}$) into fiber2 alone, which is then attenuated further by the amount L_{fiber1} upon passage back through fiber1. This is equivalent to raising the SBS threshold for the heterogeneous fiber span comprised of fiber1 and fiber2 by a little more than L_{fiber1}, depending on where the threshold is defined. Eventually, as the length of fiber1 increases, the SBS threshold of this fiber piece decreases, and it will start to generate a non-negligible amount of reflected Stokes power as well. At this point, the effective increase in SBS threshold of the heterogeneous span stops growing and begins to turn back over. The model prediction of the SBS threshold increase relative to that of the main transmission fiber alone is shown in Figure 3 for a long (304 km) length of G.654-compliant fiber (fiber2) and compared to the experimentally measured threshold values obtained from the data in Figure 1. Details of the theoretical analysis can be found in [8]. The model predicts that the optimal length of the high SBS-threshold fiber to use at the beginning of the span is about 25 km, which should result in an effective SBS threshold increase of a more than 4 dB assuming an attenuation level of fiber1 of ~0.20 dB/km. In general, the theoretical and experimental data show good agreement. Small discrepancies between the experimental results and model predictions can be explained by differences between the actual fiber characteristics and the assumptions used in the model, slightly different splice losses, etc. While the results shown in Figure 3 were derived and measured for a 304 km piece of the Vascade EX1000 fiber, we expect them to be insensitive to the exact length of this fiber for values greater than 100 km.

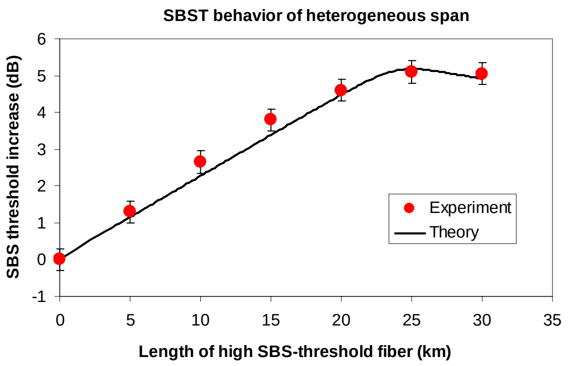

Figure 3: Model prediction and experimental results for increase in SBS threshold as a function of the length of high SBS-threshold fiber (fiber1) at the span input of a heterogeneous span comprised of fiber1 plus 304 km of the G.654-compliant fiber (fiber2)

3 EXPERIMENTAL TRANSMISSION SYSTEM RESULTS

We next turn to transmission experiments to assess the effect of the different fiber span configurations on the transmitted signal quality. The experimental transmission system set-up is illustrated in Figure 4. Up to 8 lasers were multiplexed together and modulated with a Mach-Zehnder modulator with an NRZ signal at the 10.7 Gb/s bit rate. The laser sources were undithered for all experiments. The pseudo-random bit sequence (PRBS) driving the modulator was of length 2^{31}-1. The channel(s) transmitted were amplified with a high output power EDFA and passed through a variable optical attenuator (VOA) to control the launch power into the fiber span. At the output end of the span, the channel(s) passed through 3 EDFAs with 2 stages of optical dispersion compensation modules (DCMs) in between the amplifiers. A tunable narrow optical filter (0.25 nm) selected a channel for detection in an optical receiver, which was a PIN photoreceiver with clock and data recovery. The recovered data and clock signals were passed to a bit error rate tester (BERT) for measurement of the signal BER.

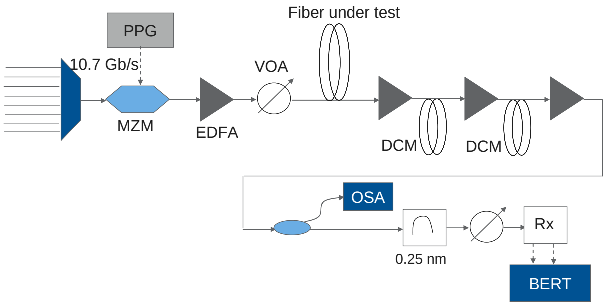

Figure 4: Schematic diagram of transmission system test set-up.

Single channel transmission experiments were first conducted using the 1550 nm wavelength through the system for fiber spans comprised of the 304 km length of Vascade EX1000 fiber in combination with various lengths of the high SBS-threshold fiber preceding it. The results are shown in Figure 5. We observe that the heterogeneous spans with higher SBS threshold due to the addition of a short piece of high SBS-threshold fiber at the span input are able to tolerate higher launch powers and achieve the same or better BER performance as the base homogeneous span of 304 km. In this way, the overall span length can be lengthened by 20-25 km with no loss in signal quality at the receiver because of the higher optimal launch powers.

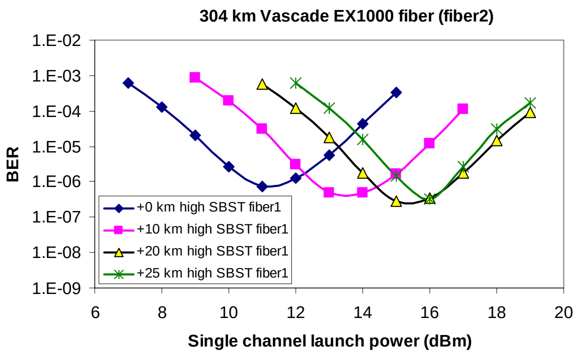

Figure 5: Transmission results for single channel launched into unrepeatered spans comprised of various lengths of high SBS-threshold G.652-compliant fiber (fiber1) and 304 km Vascade EX1000 fiber (fiber2).

It is also instructive to compare the transmission results for roughly equal overall lengths of the fiber span for the two cases when the span is constructed with homogeneous and heterogeneous designs. To that end, we performed single channel transmission experiments with a homogeneous span of 323 km of Vascade EX1000 fiber and compared it to the heterogeneous span comprised of 25 km of the high SBS-threshold fiber plus 304 km of Vascade EX1000 fiber. The results are shown in Figure 6 and illustrate the significantly better performance obtained with the heterogeneous span even though it is slightly longer by 6 km. While the total loss of each span is roughly the same, (it is slightly greater for the heterogeneous span), the higher SBS threshold of the heterogeneous span by >4 dB allows more channel power to be launched in comparison to the homogeneous span. Measured at the respective optimal channel launch powers, there is a BER advantage of over 3 orders of magnitude for the heterogeneous span.

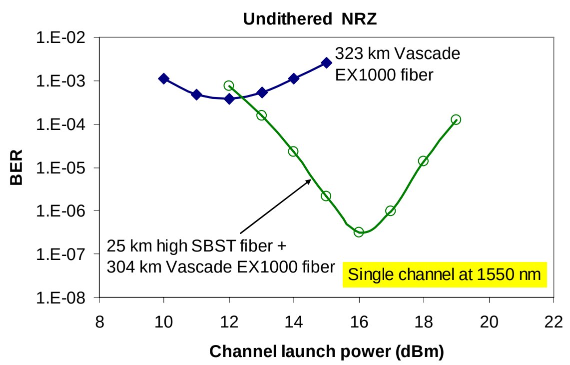

Figure 6: Experimental results comparing single channel transmission through approximately comparable length homogeneous and heterogeneous spans.

Finally, we also launched a total of 8 channels in a WDM system with 200 GHz channel spacing over the homogeneous span of 323 km of Vascade EX1000 fiber and over the heterogeneous span of 25 km high SBS-threshold G.652-compliant fiber plus 304 km Vascade EX1000 fiber. A maximum of 27 dBm total launch power was available from a high output power EDFA at the transmit end, corresponding to a maximum channel launch power of about 18 dBm. For these experiments, we also included a short piece of standard single-mode fiber before the high output power EDFA to fully de-correlate the bits in the different channels since they were simultaneously modulated with the same PRBS in the Mach-Zehnder modulator. The channel Q values as calculated from measured BER results for the 8 channels are shown in Figure 7 for both spans, for which the optimal total launch power was used in each case. We see from the figure that the heterogeneous fiber span still enjoys an advantage for the WDM system, with a Q advantage of approximately 3 dB across the channel plan at the optimal channel launch power. These results illustrate how the heterogeneous span construction can lead to significantly greater system margin for a comparable total length to a homogeneous span.

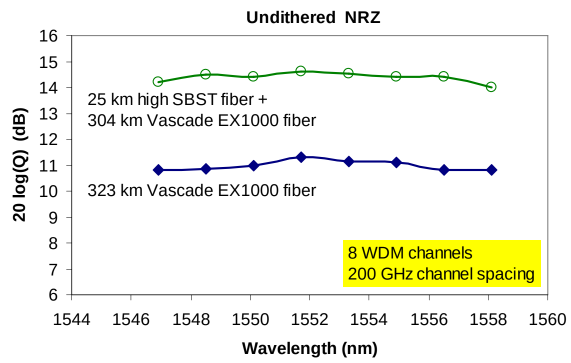

Figure 7: Q values calculated from measured BER data for the 8-channel WDM systems transmitted over a 323 km homogeneous span and a 329 km heterogeneous span.

4 SUMMARY

We have demonstrated how the addition of a short piece of high SBS-threshold fiber at the beginning of a long unrepeatered span can significantly boost the threshold of the whole composite span by more than 4 dB. For short pieces of fiber up to about ~25 km, the SBS threshold increase observed is slightly greater than the loss of the short fiber. By combining this type of fiber with a very low attenuation G.654-compliant fiber, we were able to optimize the SBS-limited performance for a total span length >300 km. In comparing the relative transmission performance between homogeneous and heterogeneous spans, we found that the addition of up to 25 km of the high SBS-threshold at the span entrance is possible with no sacrifice in signal quality with respect to the original 304 km span. Alternatively, a comparison of nearly equal length spans showed that the heterogeneous span provided significantly lower BER at the receiver in comparison to the homogeneous span for both single channel and WDM systems. The system margin over the FEC threshold for the 329 km heterogeneous span was more than 5 dB, suggesting that even longer spans may be feasible with this simple system architecture based on undithered NRZ signals and EDFA-only amplification.

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