Enlarging the Unrepeatered Transmission Length at 10Gb/s by Single Sideband Modulation and Increasing the OSNR with Raman Amplification

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ABSTRACT

In this paper we investigate the maximum unrepeatered and uncompensated transmission on standard single mode fiber (SSMF) with single-sideband (SSB) modulation. To increase the optical signal to noise ratio (OSNR) we use a backward pumping Raman source. With the combination of both the bandwidth reduced modulation scheme and the OSNR improvement with Raman amplification we can enlarge the error-free uncompensated and unrepeatered transmission length for SSB modulation up to 200km.

Keywords: single-sideband modulation, Raman amplification, uncompensated transmission, unrepeatered transmission, dispersion tolerant transmission

1. INTRODUCTION

Standard single mode fiber is the most common fiber in optical communication networks. Due to the high chromatic dispersion in the 3rd optical transmission window the bridgeable uncompensated transmission span for 10Gb/s double-sideband (DSB) modulated NRZ signal is limited to approximately 100km. To enlarge this dispersion limit, bandwidth reduced modulation schemes are required. The benefits of bandwidth reduced modulation formats are a relaxed dispersion management in WDM-systems and for high data rate systems (>10Gb/s), and also a tight channel spacing in WDM systems. Some modulation formats such as SSB, duobinary or multilevel modulation offer more dispersion tolerance than conventional DSB transmission, due to their reduced channel bandwidth [1-3]. SSB modulated signals with carrier and duobinary modulated signals can be received with a standard direct detecting receiver, whereas multilevel modulation requires a more complex receiver design.

In this paper we investigate the maximum transmission length that can be bridged by SSB modulation with carrier. No inline amplification or dispersion compensation is used. The dispersion tolerance of this modulation format is demonstrated by the maximum bridgeable transmission span. As a reference the transmission of a DSB modulated signal is observed, too.

2. SINGLE-SIDEBAND SIGNAL GENERATION

SSB modulation formats can be divided into two classes: transmission with and without carrier. This differentiation has a major impact on the receiver design that is used, i.e. in the necessary demodulation method. For a SSB signal without a carrier a coherent demodulation is necessary [8, 9]. In contrast if an incoherent receiver should be used, which is the preferred method for optical transmission, the SSB signal has to be transmitted with a carrier.

In addition, a classification can also be made concerning the method of SSB signal generation with carrier. The signal can be generated for example with optical sideband filtering of a conventional DSB signal [10, 11], or with a combination of amplitude and phase modulation, which we use in this experiment [3, 4].

Using the combined amplitude and phase modulation method to generate a SSB signal with carrier a transmitter as shown in Figure 1 is used. The transmitter consists of a conventional DSB transmitter and in addition a Hilbert transformer and a phase modulator. The SSB signal is generated in two steps. First an optical DSB signal with carrier is generated by driving a Mach-Zehnder modulator in push-pull configuration. In a second step the DSB signal is phase modulated with the Hilbert transformed electrical data signal. This yields a SSB signal.

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The combined transfer function of such a transmitter as shown in Figure 1 can be expressed as:

$$E_{out}(t)=E_{in}\cos\left(\frac{\pi}{2}\frac{m(t)-U_{bias}}{U_\pi}\right)\cdot\exp\left(j\frac{\pi}{2}\frac{\hat{m}(t)}{U_\pi}\right). \tag{1}$$

In Equation (1) E_{out} is the electrical output field, E_{in} is the electrical input field. The cosine part of Equation (1) specifies the Mach-Zehnder modulator in push-pull configuration, driven with the data signal $m(t)$ and biased with U_{bias}. The exponential part describes the phase modulation with the Hilbert transformed data signal $\hat{m}(t)$.

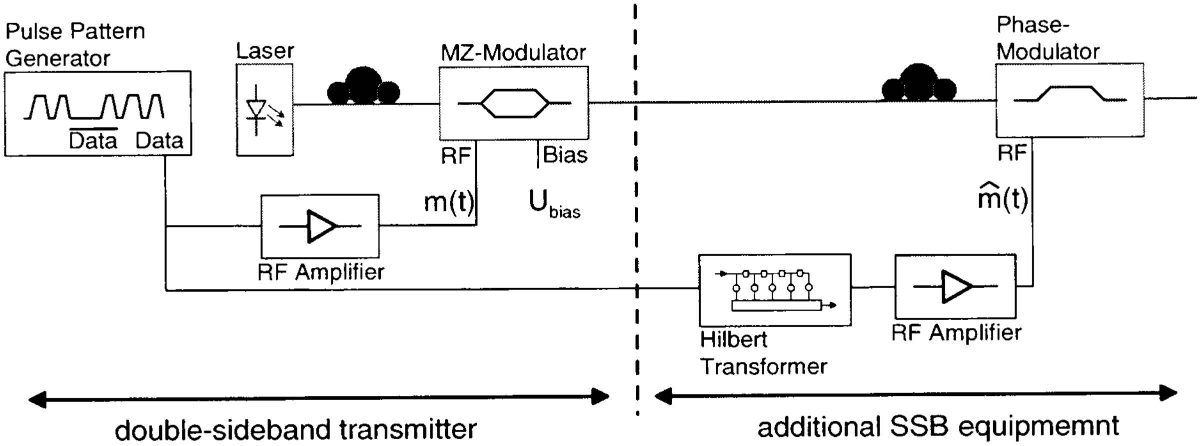

Figure 1: single-sideband transmitter; left: conventional DSB transmitter; right: additional SSB equipment

In Figure 2 (left) the transfer characteristic of the Mach-Zehnder modulator is displayed. The electrical field and the optical output power as well as the bias point and the operation range are shown. By driving the Mach-Zehnder modulator in quadrature the series expansion of Equation (1) leads to the following expression:

$$\begin{aligned}E_{out}(t)=\frac{E_{in}}{\sqrt{2}}\Bigg[&\left(1+\frac{\pi}{2U_\pi}\cdot m(t)-\frac{\pi^2}{8U_\pi^2}\cdot m(t)^2-\frac{\pi^2}{8U_\pi^2}\cdot\hat{m}(t)^2-\frac{\pi^3}{16U_\pi^3}\cdot m(t)\hat{m}(t)^2+\frac{\pi^4}{64U_\pi^4}\cdot m(t)^2\hat{m}(t)^2+\ldots\right)\\&+j\cdot\left(\frac{\pi}{2U_\pi}\cdot\hat{m}(t)+\frac{\pi^2}{4U_\pi^2}\cdot m(t)\hat{m}(t)-\frac{\pi^3}{16U_\pi^3}\cdot m(t)^2\hat{m}(t)+\ldots\right)\Bigg]\end{aligned}. \tag{2}$$

By retaining only the first order terms of Equation (2) (this is approximately equivalent to a linear driving of the modulators) it can be seen that a SSB signal is generated. The signal consists of a carrier and the analytical signal:

$$E_{out}(t)=\frac{E_{in}}{\sqrt{2}}+\frac{E_{in}}{\sqrt{2}}\cdot\frac{\pi}{2U_\pi}\cdot\left[m(t)+j\hat{m}(t)\right]+\ldots. \tag{3}$$

At the receiver the signal is detected by a photodiode with an absolute square law detection. Assuming a fiber length of 0km (back-to-back condition) the received signal, starting from Equation (2), is:

$$|E_{out}(t)|^2 = \frac{|E_{in}|^2}{2} + \frac{|E_{in}|^2}{2} \cdot \frac{\pi}{U_\pi} \cdot m(t) + \ldots \tag{4}$$

Equation (4) shows that the transmitted data signal $m(t)$ can be directly recovered with a standard receiver.

The Hilbert transformation of the electrical data signal is done by a finite impulse response (FIR) filter [5]. This FIR filter approximates a Hilbert transformer. The principle layout of such a Hilbert transformer is illustrated in Figure 2 (right). The delay time is T=100ps for a 10Gb/s signal. Investigations by simulations show, that even with only 2 coefficients a good sideband suppression can be achieved. Such a Hilbert transformer with only two coefficients is used in the experimental and simulation setup.

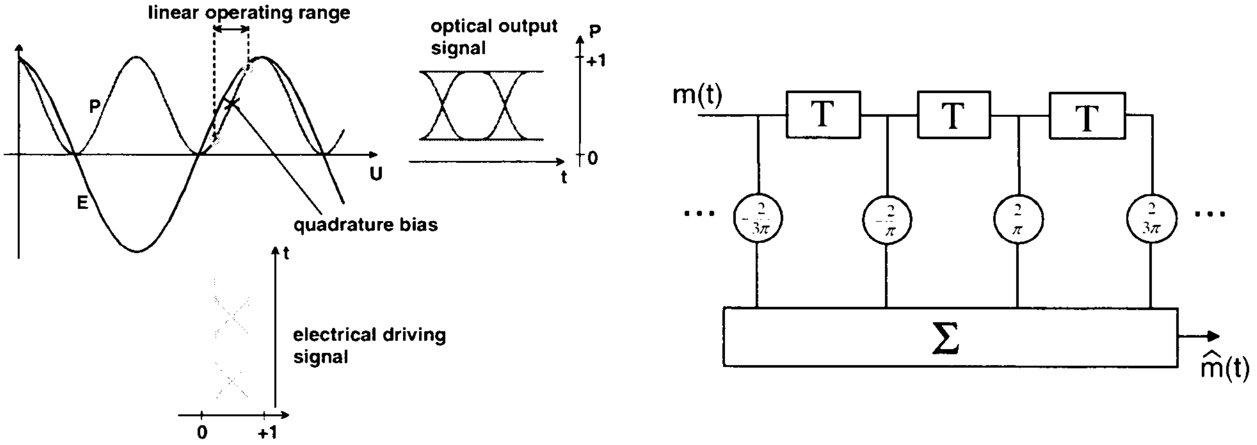

Figure 2: left: transfer characteristic of the Mach-Zehnder modulator; right: tapped delay line Hilbert transformer.

The resulting optical SSB spectrum as shown in Figure 3 has a strong attenuated sideband. The results of the simulated spectrum (Figure 3 left) and the measured spectrum (Figure 3 right) show a good qualitative agreement. The measured spectrum was recorded with a resolution bandwidth of 0.01nm. In comparison to the SSB spectrum a fully driven DSB spectrum is displayed. A large bandwidth reduction is obvious. This leads to an improved dispersion tolerance resulting in an enlarged bridgeable transmission span.

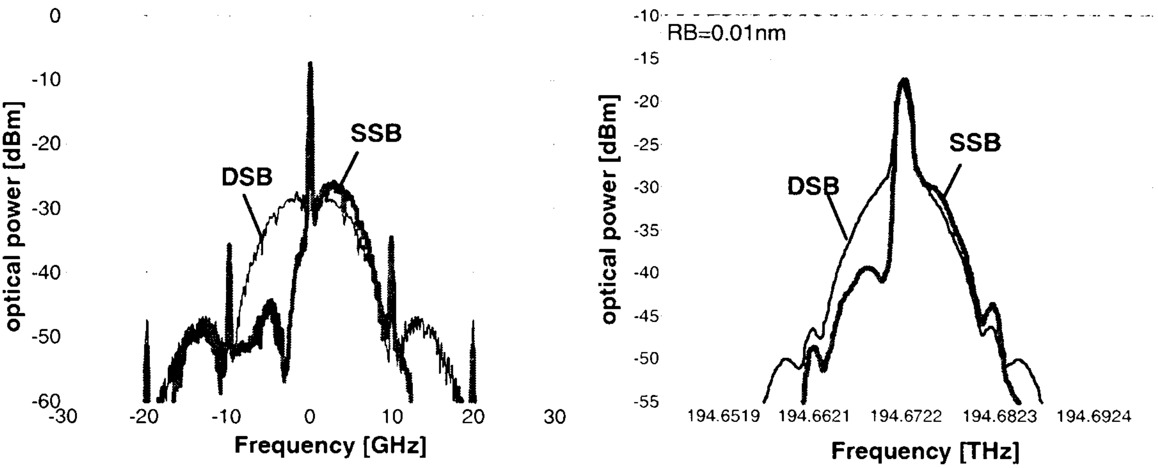

Figure 3: optical power spectral density (left: simulation, right: measurement) thick line: single-sideband modulation, thin line: double-sideband modulation

3. TRANSMISSION CHARACTERISTICS

Due to the linear driven Mach-Zehnder modulator the measured extinction ratio is reduced to roughly 5dB. The measured extinction ratio of a fully driven Mach-Zehnder modulator is in our case about 13dB. Thereby the SSB signal has a significant back-to-back penalty in comparison to conventional DSB transmission. In Figure 4 the simulated transmission performance of a SSB signal and a conventional DSB signal on a linear SSMF is shown. The simulated standard single mode fiber has a dispersion of 17ps/(nm km) and a dispersion slope of 0.06ps/(nm^2 km). The simulated photodiode has a 3rd order butterworth lowpass characteristic with a 3dB cutoff frequency of 7GHz. The Hilbert transformer is approximated in the simulation by a FIR filter with 2 coefficients. In Figure 4 (left) the simulated eye diagrams of DSB and SSB modulated signals are displayed. The eye diagram of the DSB modulated signal is closed after 150km transmission on standard single mode fiber, whereas the eye diagram of the SSB modulated signal shows an open eye up to 250km. In Figure 4 (right) the eye opening penalty as a function of transmission length is shown. Up to 100km the SSB eye opening penalty is higher than by using conventional DSB modulation. At about 100km the eye opening penalties of the modulation formats are nearly in the same order of magnitude, and beyond 100km the SSB eye opening penalty is lower than the penalty of the DSB signal. So the SSB signal shows a large dispersion tolerance in comparison to the DSB signal.

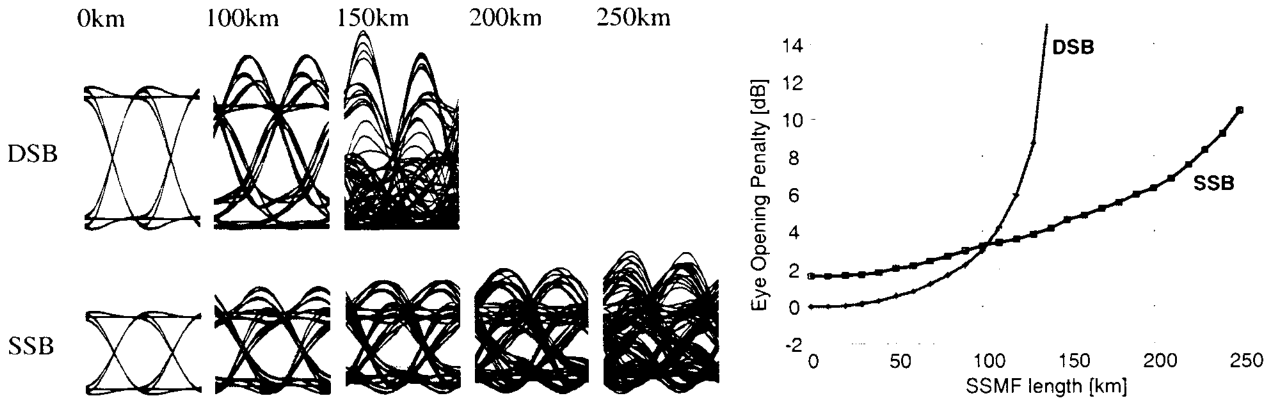

Figure 4: simulation of the linear transmission of SSB and DSB signals; left: eye diagrams of DSB modulation and SSB modulation; right: eye opening penalty as a function of transmission length.

4. PRINCIPLES OF RAMAN AMPLIFICATION

The principle of Raman amplification is a power transfer from the pump channel (shorter wavelength) to the signal channel (longer wavelength) [6, 7].

The Raman pump used in our setup has an operation wavelength of 1455nm. The optical output power of the used pump is about 29dBm. In Figure 5 the measured spectrum at the fiber output with Raman amplification is shown. As a result of the used booster and preamplifier erbium doped fiber amplifier (EDFA) transmission window the signal wavelength could not be set to the maximum gain of the Raman amplifier. In order to characterize the performance of the Raman amplifier the ON-OFF gain is measured. With this Raman source an ON-OFF gain of about 25dB is achieved. This is exemplified by plotting the signal power along the fiber in Figure 6 (left). The signal launch power was set to 0dBm. After 150km a received power of –34.6dBm is

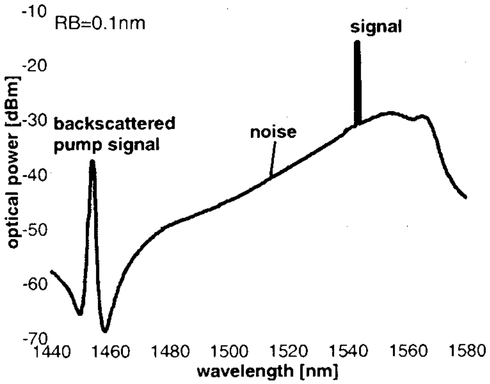

Figure 5: optical spectrum at fiber output with Raman amplification.

measured without Raman amplification, and –9.6 with Raman amplification. The ON-OFF gain does not reveal the optical signal to noise ratio, and so it does not reflect the transmission improvement. The measured OSNR improvement, for the 150km link, is about 10dB (Figure 6 right).

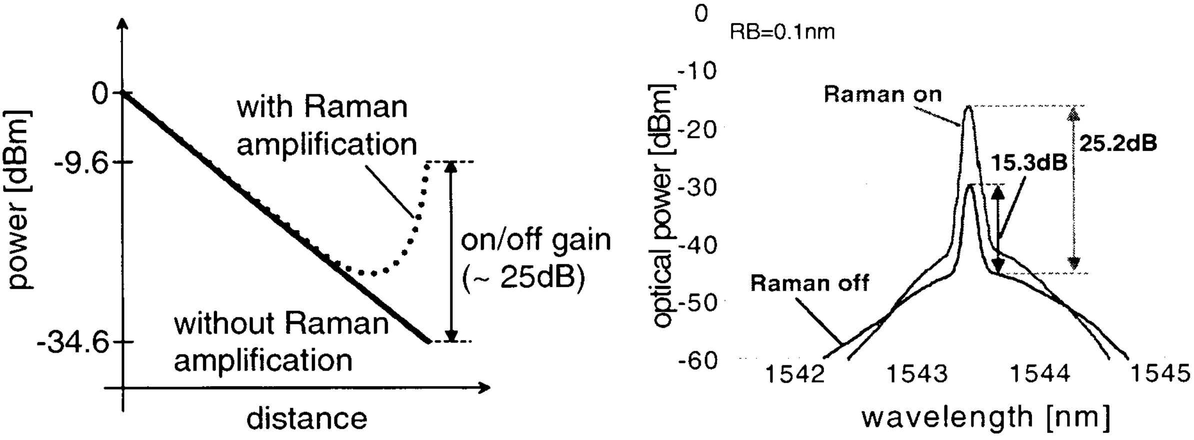

Figure 6: left: power-budget of a Raman pumped 150km transmission link; right: measured signal spectrum with and without Raman amplification at the end of the transmission link (resolution bandwidth = 0.1nm).

5. EXPERIMENTAL SETUP

The setup of the transmission experiment is shown in Figure 7. The Mach-Zehnder modulator in the conventional DSB transmitter is fully driven, if binary signals are observed.

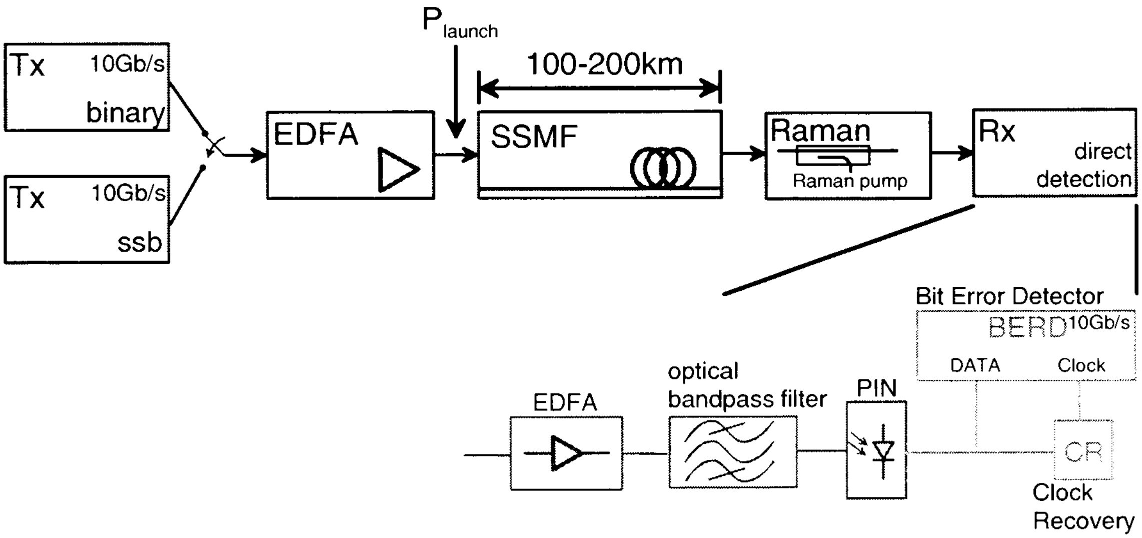

Figure 7: experimental transmission setup.

The laser we have used in the transmitter is a DFB laser at an operation wavelength of 1544nm. After signal generation in the transmitter the signal is amplified by a booster EDFA. The length of the standard single mode fiber is varied from 100km up to 200km. A backward pumping Raman source is placed at the end of the fiber to improve the transmission performance. The signal is received by a standard preamplified direct detection receiver. After signal amplification in the preamplifier EDFA the optical signal is bandpass filtered, to reduce the amplified spontaneous emission (ASE) noise of the EDFA. The clock signal, which is necessary for bit error ratio (BER) measurements, is recovered in a separate electrical clock recovery.

In this transmission experiment we investigate the maximum unrepeatered and uncompensated transmission length with a SSB signal. To improve the OSNR and to amplify the optical signal we use a Raman source. In order to quantify the system improvement with backward Raman amplification the BER is measured as a function of optical launch power into the fiber.

6. MEASUREMENT RESULTS

In order characterize to the system improvement we measure the BER as a function of optical launch power into the fiber. The output power of the backward pumping Raman source was held at a constant level of 29dBm for all measurements with Raman amplification. The operation wavelength of the Raman pump source was 1455nm. The optical signal carrier wavelength was set to 1544nm.

Performance of SSB modulation:

First of all, we measure the BER as a function of different fiber lengths for SSB modulation. The Raman source is switched off in this measurement. The results for uncompensated and unrepeatered transmission on SSMF for 0km, 100km 150km and 175km are displayed in Figure 9 (left). Up to 175km an error free transmission is possible. By launching more than 11dBm into the fiber self-phase modulation (SPM) degrades the BER, so the maximum uncompensated and unrepeatered transmission length without Raman amplification is limited to 175 km.

Performance of SSB modulation and Raman amplification:

Now we investigate the transmission performance with the Raman pump source switched on. The impact of Raman amplification is displayed in Figure 8. As a reference the DSB signal is plotted as well as the SSB signal. As we have seen above, the back-to-back performance of SSB modulation is degraded in comparison to a DSB signal. After 100km the performance of the DSB and the SSB modulated signals are nearly in the same order of magnitude. This behavior shows a good correspondence to our simulation results. By switching the Raman source on both BER curves are shifted towards lower launch power. The BER improvement is in the same order of magnitude as the OSNR improvement (see Figure 10). The plotted spectra of the DSB and the SSB signal show an OSNR improvement of about 10dB. Therefore we can conclude, that the OSNR improvement is independent of the modulation format.

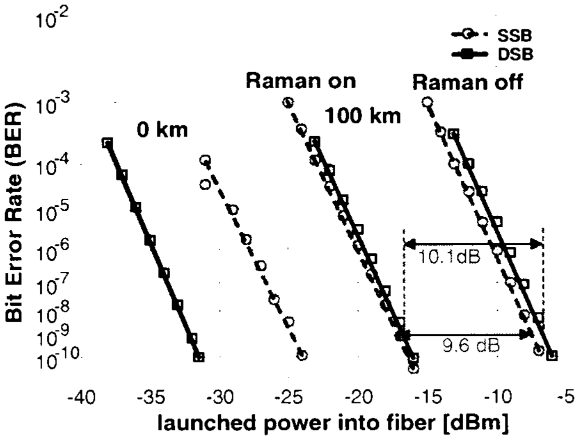

Figure 8: BER of single-sideband and double-sideband signals with and without Raman amplification.

The maximum unrepeatered and uncompensated error-free transmission length with Raman amplification we have measured is 200km (see Figure 9 right). The BER improvement by using the Raman pump source is in the same order of magnitude as the OSNR improvement. This is independent of the transmission length. In Table 1 the OSNR improvement and the BER improvement of SSB modulation with Raman pump source is listed. Due to the signal degradation of chromatic dispersion the necessary OSNR for error-free transmission increases for longer transmission lines.

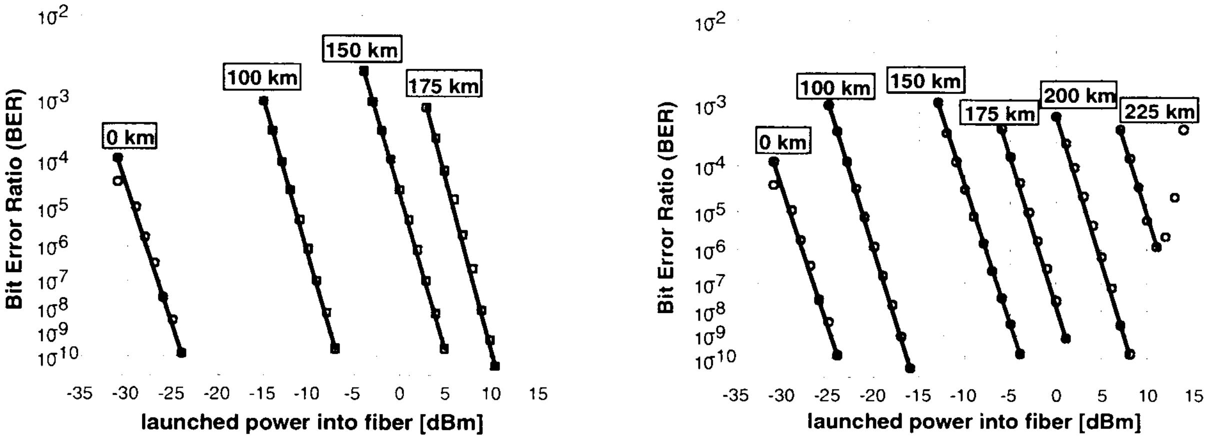

Figure 9: left: single-sideband transmission without Raman amplification, error-free transmission up to 175km; right: single-sideband transmission with Raman amplification, error-free transmission up to 200km

In the case of 175km transmission the improvement is 1dB less than in the other cases, due to the BER improvement by SPM [3] by transmitting with high launch power. By transmitting 225km only a BER of $1.3 \cdot 10^{-6}$ could be achieved with a launch power of 11dBm. If more input power is launched into the fiber, the BER is degraded rapidly because of SPM.

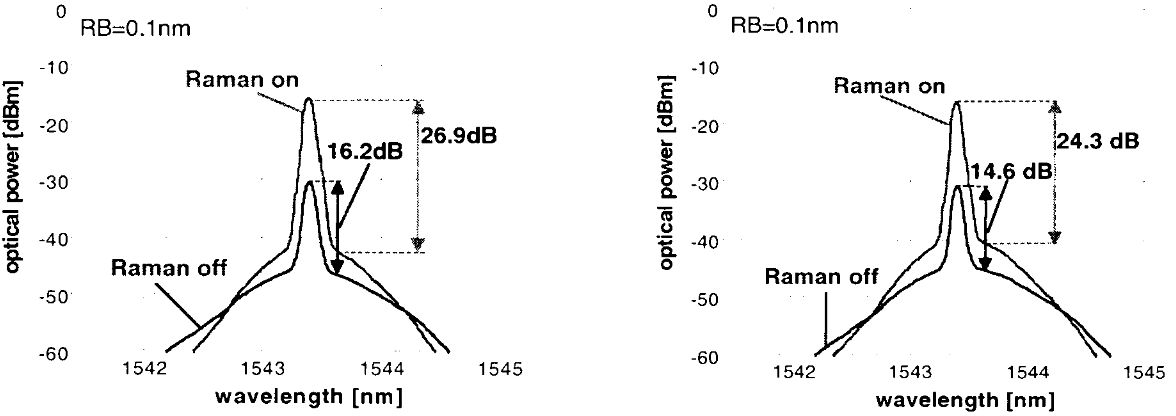

Figure 10: left: measured spectra of the double-sideband signal; right: measured spectra of the single-sideband signal. The OSNR improvement is about 10dB. (resolution bandwidth=0.1nm)

The received SSB eye diagrams are shown in Figure 11. The eye diagrams are recorded after 100km, 150km,175km and 200km. The used photodiode to record the eye diagrams has a bandwidth of 12GHz. A well open eye diagram is observed up to 200km.

transmission length	100km	150km	175km	200km
OSNR Raman off	14.6	15.3	16.2	not error free
OSNR Raman on	24.3	25.2	26.2	27
OSNR improvement	**≈9.7**	**≈9.9**	**≈10**	
BER improvement	**≈9.6**	**≈9.5**	**≈8.6**	

Table 1: OSNR and BER improvement by using a Raman amplifier.

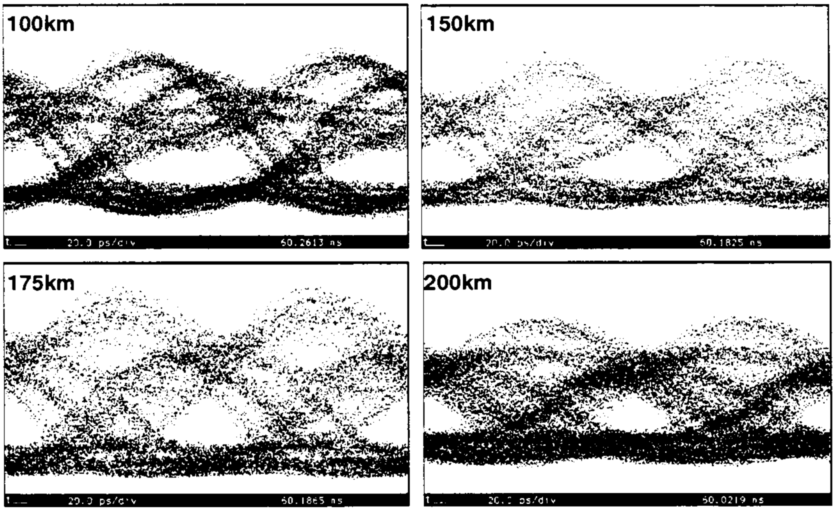

Figure 11: received eye diagrams for single-sideband transmission with Raman amplification, upper row: 100km and 150km transmission, lower row: 175 and 200km transmission.

7. CONCLUSION

We have investigated the maximum transmission length without any inline amplification and without dispersion compensation, when a SSB signal with carrier is used. We have used a Raman pump source at the end of the fiber link to improve the signal power and the optical signal-to-noise ratio. The maximum link length without Raman amplification was 175km with a launch power of about 10.5dB. By launching more power into the fiber the transmission is limited by self-phase modulation. With Raman amplification the necessary launch power for error-free transmission decreases in the same order of magnitude as the OSNR increases. The maximum error-free transmission length was enlarged to 200km.

Up to 100km SSB modulation requires more launch power than DSB modulation for error-free transmission. Beyond 100km SSB modulation requires less launch power than DSB modulation, and the unrepeatered and uncompensated transmission length is doubled. SSB modulation offers a better dispersion tolerance due to the reduced channel bandwidth.

8. REFERENCES

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