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Cost-effective 10.7-Gbit/s Long-Haul Transmission using Fiber Bragg Gratings for In-line Dispersion Compensation

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Abstract: We show the feasibility of more cost-effective long-haul transmission using Fiber Bragg Gratings (FBG) for in-line dispersion compensation. 32x10.7-Gbit/s NRZ modulated channels are transmitted over 40x95 km of SSMF using low group delay ripple FBGs.

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1. Introduction

Among the promising developments towards more cost-effective long-haul transmission solutions are chirped multi-channel fiber Bragg gratings (FBGs) [1-2]. FBGs could replace the currently used dispersion compensation fiber (DCF) for in-line dispersion compensation. DCF is currently the standard solution for use in long-haul transmission links since it yields colorless, slope-matched dispersion cancellation with negligible cascading impairments. However DCF is also limited in optical input power to avoid nonlinear impairments, has a relatively high insertion loss and is bulky.

Chirped FBGs on the other hand have a negligible nonlinearity, low insertion loss and small size. This potentially allows simpler erbium-doped fiber amplifier (EDFA) design by cascading the FBG and transmission fiber without a mid-stage amplifier, resulting in a significant cost reduction. The main drawback of FBGs is that they suffer from distortions in their phase response, better known as the group delay ripple (GDR) [3]. This is caused by imperfections in the gratings fabrication process and limits the number of FBGs that can be cascaded. Improved fabrication processes have however gradually reduced the GDR of state-of-the-art slope-matched FBGs, which significantly increases the number of FBGs that can be cascaded [4].

In this paper we show, to the best of our knowledge for the first time, long-haul WDM optical transmission using only FBGs for in-line dispersion compensation. We successfully transmit 32x10.7-Gbit/s NRZ modulated channels over 3,800 km using low-GDR slope-matched FBGs to compensate for the in-line group-velocity dispersion (GVD).

2. Experimental setup

Fig. 1 depicts the re-circulating loop setup. In this experiment 32 distributed feedback laser (DFB) outputs are combined on a 100-GHz ITU grid, from 1538.2 THz to 1563.0 THz. Using a standard Mach-Zehnder modulator (MZM) the signals are NRZ-OOK modulated with a 10.7-Gbit/s $2^{31}-1$ pseudo-random bit sequence (PRBS).

Fig. 1: Experimental setup; circ: Circulator, AOM: acoustic optical modulator.

The re-circulating loop used in the transmission experiment consist of 8 x 95-km SSMF spans. The average loss of the SSMF spans is 19.5 dB and the FBG-based dispersion compensation modules (DCM) have an average insertion loss of 2 dB. EDFA-only amplification is used, with double-stage EDFAs to control the tilt of the WDM spectrum. The SSMF input power is 3 dBm per WDM channel. A double periodic dispersion map is used in the transmission experiments. This has the advantage that the accumulated dispersion after every eight spans is close to zero [5]. Before the first span a FBG-based DCM with -1020 ps/nm of GVD (at 1550 nm) is used as pre-compensation. For inline dispersion compensation, the DCMs have a GVD equivalent to 80 km (-1345 ps/nm, 5x) or 100 km of SSMF (-1681 ps/nm, 3x). Loop-induced polarization effects are reduced using a loop-synchronous polarization scrambler (LSPS). Power equalization of the DWDM channels is provided by a channel-based dynamic gain equalizer (DGE).

At the receiver the desired WDM channel is selected using a narrowband 18-GHz channel-selection filter (CSF) and the residual GVD is per-channel optimized with a tunable dispersion compensator (TDC) (DCF/SSMF-based). Afterwards the signal is fed to a standard 10.7-Gbit/s receiver (Rx) and evaluated using a bit-error rate (BER) tester.

3. Experimental results

Fig. 2a and 2b show the measured Q-factor after 3,040-km and 3,800-km of transmission, cascading 36 and 45 FBGs, respectively. The influence of GDR-related impairments is apparent through the large (~5 dB) spread in performance between the WDM channels. For a similar DCF-based transmission experiment the spread in Q-factor is expected to be in the range of ~1 dB (see for example [6]). Yet after 3,040-km transmission the measured Q-factor for the worst channel is still 2.5-dB above the correction limit of a concatenated FEC code with a 7% overhead (BER $2.4 \cdot 10^{-3}$ or Q-factor 9.0 dB). And even for a 3,800-km transmission distance the measured Q-factor is above the FEC limit for all 32 channels.

Fig. 2: Measured Q-factor for 32 WDM channels after (a) 3,040-km and (b) 3,800-km transmission.

Fig. 3: upper row: Eye diagrams after 3,800 km with small (a and b) and large (c and d) GDR related penalties, lower row: simulated back-to-back eye diagrams using measured amplitude and phase response.

Fig. 3 shows in the upper row the measured eye diagrams after 3,800-km of transmission for several WDM channels. The eye diagrams at 1543.7 nm (a) and 1551.7 nm (b) show WDM channels where the GDR has a relatively small influence. On the other hand, for the channels at 1552.5 nm (c) and 1554.1 nm (d) a severe influence of GDR is evident, limiting the feasible transmission distance to 3,800 km. The lower row in Fig. 3 shows the eye diagrams for the same WDM channels when the amplitude and phase response of the cascaded FBGs is simulated. In the simulations the measured amplitude and phase response of the FBGs from the transmission experiment are used, but no transmission is simulated ("back-to-back"). Hence, the simulation shows only the GDR related

impairments resulting from the cascaded FBGs. Both the simulated and measured eye diagrams in Fig. 3 show a strong broadening of the '1'-rail through phase distortions. Based on this similarity we conjecture that the phase distortion result mainly from GDR induced penalties.

Back-to-back, the required optical signal-to-noise ratio (OSNR) is 9.7 dB and 15.3 dB for a Q-factor of 9.8 dB (BER 10^{-3}) and 15.6 dB (BER 10^{-9}), respectively. After transmission the average OSNR is 19.7 dB and 18.8 dB, for respectively a 3,040-km and 3,800-km transmission distance. The OSNR penalty is computed by comparing the required OSNR back-to-back and after transmission for the best-case and worst-case measured Q-factor. After 3,040 km transmission the OSNR penalty is between 4 dB and 8.5 dB, and for a 3,800-km transmission distance the penalty ranges from 5 dB to 10 dB. Fig. 4a and 4b shows the Q-factor decrease with transmission distance for respectively a channel with small and large GDR penalties. The Q-factor decreases with ~ 6.5 dB when the transmission distance is doubled, in comparison to 3 dB for an ideal (linear) transmission line. Hence, the GDR related impairments become more severe with an increasing number of cascaded FBGs.

In the re-circulating loop experiments the measured penalty is however artificially increased due to the cascade of the same FBGs, resulting in a correlated GDR. This is visualized by the simulation in Fig. 4c and 4d, which show the growth of the peak-to-peak GDR (GDRpp) when an increasing number of FBGs is cascaded. The mean value and the standard deviation of the GDRpp are computed from a large number (>100) of FBGs for statistical averaging. Both the mean GDRpp and the mean GDRpp plus twice the standard deviation (2σ) are shown. In Fig. 4c arbitrary cascaded FBGs are shown, as occurs in field deployment. Fig. 4d depicts the case when 8 arbitrary FBG are cascaded in a re-circulating loop. For arbitrary cascaded FBG the GDR is uncorrelated and as a result the influence of the GDR grows statistically (square-root) [7]. However in this transmission experiment 8 FBGs are cascaded in a re-circulating loop and the optical signal is thus passed multiple times through the same FBG. Consequently, the peak-to-peak GDR grows linearly, tremendously worsening the associated penalty (Fig. 4d). Hence, we conjecture that for arbitrary cascaded FBGs the drop-off with transmission distance is less steep and a significant larger number of FBGs can be cascaded with acceptable GDR related impairments.

Fig. 4: Measured Q-factor versus distance for a channel with small (a) and large (b) GDR penalties as well as several arbitrary WDM channels (grey); Peak-to-peak group-delay ripple (c) when arbitrary FBGs are cascaded and (d) when 8 FBGs are cascaded in a re-circulating loop.

4. Conclusions

We showed for the first time long-haul 10.7-Gbit/s WDM transmission with only FBG-based DCMs for in-line dispersion compensation. Using low-GDR FBGs we successfully transmit NRZ modulated data over 40 x 95 km, cascading 45 FBG units. The penalties associated with cascading a large number of FBGs (>30) implies that FBGs are not yet suitable for ultra long-haul applications. But it shows that FBG fabrication technology has matured into an appealing alternative for cost-sensitive long-haul links, up to approximately 2000 km.

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