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

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Among the promising new developments towards cost-effective long-haul transmission are chirped multi-channel Fiber Bragg Gratings (FBG). In this paper we discuss the feasibility of long-haul WDM optical transmission using only FBGs for in-line dispersion compensation. We show successful transmission of 32x10.7-Gbit/s NRZ modulated channels over 3,800-km using low group delay ripple slope-matched FBGs.

Introduction

Dispersion compensating fiber (DCF) is currently used as the standard solution for dispersion compensation 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 could possibly replace DCF as the standard solution for in-line dispersion compensation. Chirped FBGs have a negligible nonlinearity, low insertion loss and small size [1-2]. 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 group-velocity dispersion (GVD).

Chirped multi-channel fiber Bragg gratings

Chirped multi-channel FBGs can compensate for the group velocity dispersion of single-mode fibers due to a frequency dependent group delay. The dispersion compensation module (DCM) consists of a circulator and a FBG, as depicted in Fig. 1. The FBGs used in the experiments have a 100-GHz channel spacing and Fig. 2b and 2c show the amplitude and phase response for a single WDM channel of the FBG, respectively. The group delay is relatively linear over

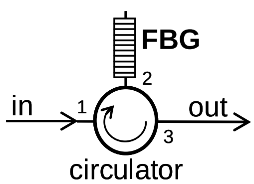


Fig. 1: Layout of the FGB-based DCMs

approximately a 70-GHz bandwidth within the 100-GHz WDM channel spacing . The FBG 's GDR can be computed by taking a linear fit of the group delay, and computing the deviations from this linear fit (Fig. 2c). The FBGs used in the described experiments have an average peak-to-peak GDR of 15.5 ps within a 35-GHz bandwidth around the channel's center.

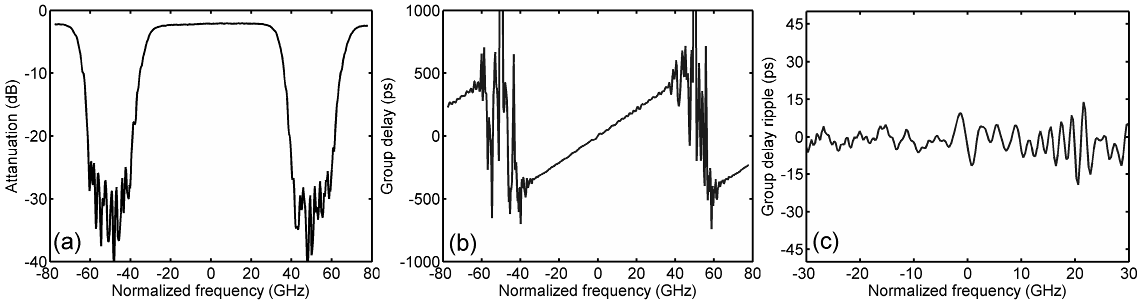


Fig. 2: Measured response of a chirped multi-channel FBG for one particular WDM channel;(a) attenuation, (b) group delay and (c) group delay ripple.

Experimental setup

Fig. 3 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). 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 DCMs 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.

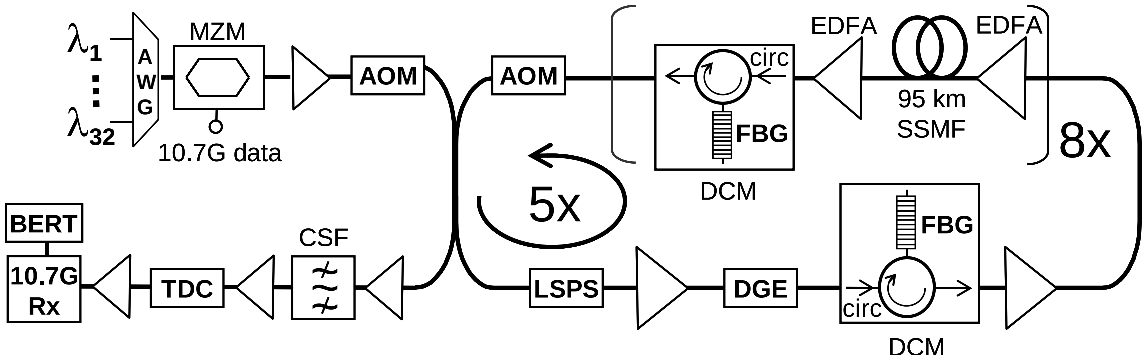


Fig. 3: Experimental setup; circ: Circulator, AOM: acoustic optical modulator.

Experimental results

Fig. 4a and 4b 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.

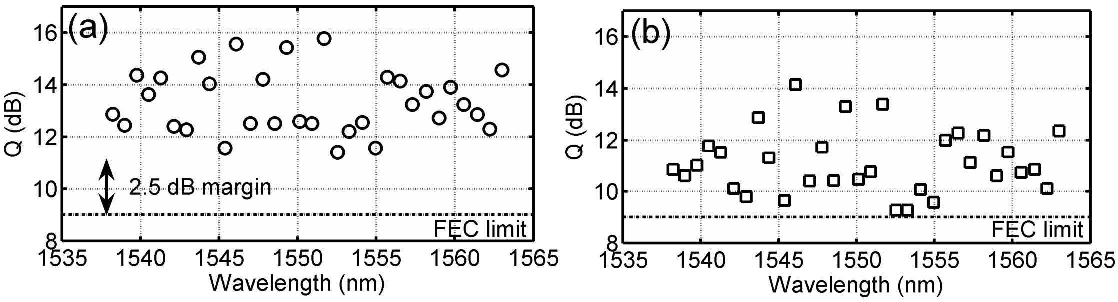
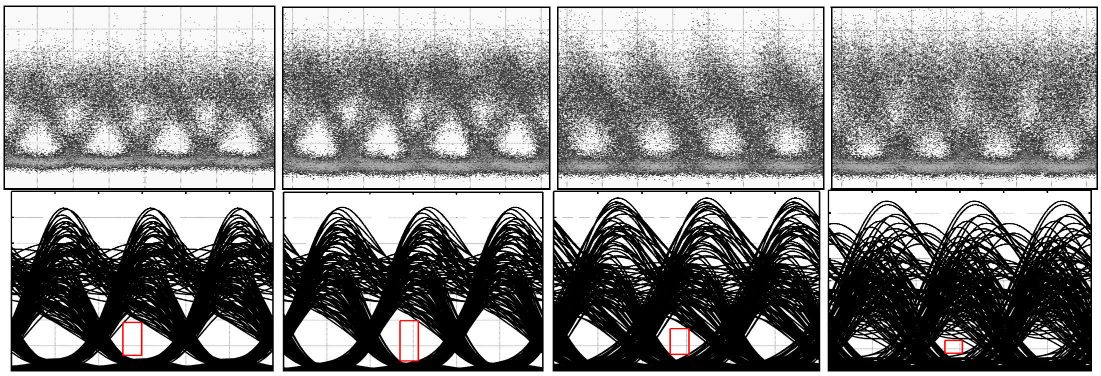


Fig. 4: Measured Q-factor for 32 WDM channels after (a) 3,040-km and (b) 3,800-km transmission.



(a) 1543.7nm **(b) 1551.7nm** **(c) 1552.5nm** **(d) 1554.1nm**

Fig. 5: upper row: Eye diagrams after 3,800 km with small (a and b) and large (c and d) GDR related penalties, lower row: simulated eye diagrams using measured amplitude and phase response.

Fig. 5 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. 5 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 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. 5 show a strong broadening of the '1'-rail through phase distortions. Based on this similarity we conjecture this 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. 6a and 6b 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. As a result 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. 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. 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 impairments.

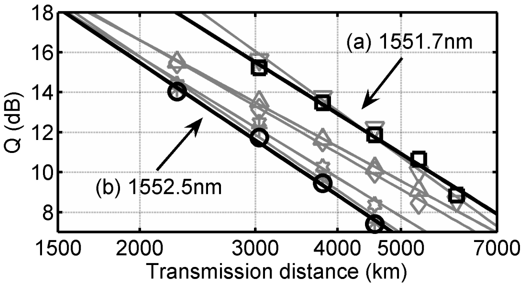


Fig. 6: Measured Q-factor versus distance for a channel with small (a) and large (b) GDR penalties as well as several arbitrary WDM channels (grey).

Conclusions

We showed 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 links, up to approximately 2000 km.

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