Group-velocity Dispersion Compensation of Telecom Data Signals using Compact Discrete Phase Filters in Silicon

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Abstract: We propose a discrete phase filter design suitable for group-velocity dispersion compensation of data signals in fiber-optics telecommunication links using waveguide Bragg gratings in silicon. Dispersion compensation of a 24-Gbps NRZ-OOK signal after propagation through 31.12 km of SMF is experimentally demonstrated using mm-long phase filters. © 2021 The Author(s)

Rapid advancements in both ultra-wideband optical-amplifier technology and advanced modulation formats has expanded the capacity of single mode fiber (SMF)-based optical links to excess of 150 Tb/s [1]. Despite these improvements, chromatic or group-velocity dispersion (GVD)-induced broadening/distortion of the data signals still remains a key impairment in wavelength division multiplexing (WDM)-based optical links, especially over medium-reach distances (such as in Passive Optical Networks, PONs) and long haul networks. Typically, GVD-induced signal degradation in WDM-based optical links is compensated for by employing either receiver-side equalization techniques based on digital signal processing (DSP) [2], or through an optical (i.e., analog) linear dispersion management scheme comprising of dispersion compensating fiber (DCF) with an opposite GVD profile. DSP-based dispersion compensation is a computationally expensive task, leading to undesired power consumption as well as introducing significant latency in the overall optical link. On the other hand, DCFs generally require 10s of kms of fiber length, leading to non-zero insertion loss and additional latency in the link. Alternatively, fibre Bragg gratings (FBGs) can compensate for large amounts of GVD in significantly more compact forms (e.g., 10s of cm fiber device lengths over a single WDM channel), but they require the use of additional components for retrieving the reflected signal (e.g., optical circulators), ultimately resulting in bulky setups. Thus, a highly-desired solution would involve the use of a compact integrated (on-chip) optical GVD line, which could be directly integrated in pluggable-transceivers. Towards this aim, linearly chirped waveguide Bragg gratings (LCWBGs) have been suggested as a potential solution for GVD compensation [3]. However, in an LCWBG, the spectral phase accumulation that is inherent to the design limits the net amount of GVD that can be compensated for over a prescribed operation bandwidth (BW) as a larger overall phase excursion translates into a longer device. In particular, compensation of the GVD profile of a standard SMF with length just above 20 km over a 100-GHz WDM channel would require a LCWBG with a length well above 1 cm. This is a difficult target to realize in practice due to intrinsic waveguide losses and the inherent grating phase noise that is induced over longer device lengths due to fabrication imperfections (e.g., random fluctuations in waveguide width). Recently, we have introduced a discrete phase filter design framework using WBGs wherein the continuous spectral phase function of a target GVD is discretized and bounded within a $[0, 2\pi)$ range [4, 5]. Using this technique, spectral phase accumulation is avoided leading to a significant reduction in device length compared to conventional designs, e.g., LCWBGs. In this communication. we propose and demonstrate the use of the discrete phase filtering process for dispersion compensation of continuous-time aperiodic waveforms, such as the data signals used in a fiber-optics telecommunication link. In experiments, we show GVD compensation of a 24-Gbps non-return-to-zero on-off keying (NRZ-OOK) pseudo-random data signal after propagation through a 31.12 km long section of a standard SMF using mm-long on-chip phase filters in a silicon-on-insulator (SOI) platform. The reported design provides a device length reduction by at least 5× compared to an LCWBG. We believe this is the first demonstration of linear GVD dispersion compensation in a fiber-optics telecommunication link using a silicon-photonics chip.

We target second-order dispersion (SOD) compensation in a fiber-optics link characterized by a SOD coefficient β_2 and of length L, over a full frequency bandwidth $\mathrm{BW}_{30\text{-dB}}$. Towards this aim, we propose using a discrete and bounded spectral-phase filter, with a frequency resolution $\omega_r = 2\pi\upsilon_r$. We predict that the discrete phase filter will effectively emulate the continuous spectral phase profile of the target dispersive line, i.e., $\phi(\omega) = -(\beta_2 L/2)\omega^2$, as long as this phase profile remains approximately constant over the filter's frequency resolution. Here, ω is the baseband frequency variable. This condition can be expressed mathematically as

$$\Delta\phi(\omega) \approx |\beta_2|L\omega_r\omega \ll \pi \tag{1}$$

Eqn. 1 should be satisfied over the full operation bandwidth, which translates into the following condition

$$2\pi|\beta_2|L\omega_r \mathrm{BW}_{30-\mathrm{dB}} = \Delta\tau_g\omega_r \ll 2\pi \tag{2}$$

where $\Delta\tau_g = 2\pi \cdot |\beta_2| \cdot L \cdot BW_{\text{30-dB}}$ is the net group-delay excursion of the target dispersive line. Eqn. 2 implies that the maximum group-delay excursion that can be emulated with the proposed discrete phase filtering approach is inversely proportional to the frequency resolution of the filter. To confirm this, we have carried out system-level simulations (i.e., Q-factor and BER estimates) of discrete phase filters designs with varying ν_r, aimed at compensation of the SOD introduced by SMF sections with different lengths. Recall that the Q-factor is defined as the difference of the mean values of the two signal levels (a '0' and a '1' bit) divided by the sum of the noise standard deviations at the two levels. The BER is estimated from the Q-factor as BER$=\frac{1}{2}\,\text{erfc}(Q/\sqrt{2})$ [6]. First, we consider SOD compensation of a 2^{15}-1 pseudo-random bit sequence (PRBS) 50-Gbps NRZ-OOK data signal. For these simulations, we assume that the fiber-optics link consists of an ideal transmitter and receiver (i.e. with zero additional noise). The calculated Q-factor of the output signal after compensation from each of the considered discrete phase filters is plotted for different SMF lengths (L_{SMF}) in Fig. 1(a). As expected, for a given Q-factor, phase filter designs with a smaller ν_r can compensate for a larger $\Delta\tau_g$. For an output BER ~ 10^{-9}, a discrete phase filter design with ν_r =10 GHz can compensate for a 16 km long segment of a standard SMF, compared to up to 40 km, in the case of a phase filter with ν_r =1 GHz. Nonetheless, this analysis also shows that the aforementioned relation in Eqn. 2 is far too restrictive, and can be significantly relaxed depending on the receiver sensitivity. As observed in Fig. 1(b), the performance of a phase filter design, for a fixed ν_r (e.g., 10 GHz in the shown example), improves proportionally with a reduction in the input bit rate (or the corresponding signal BW) for varying values of L_{SMF}.

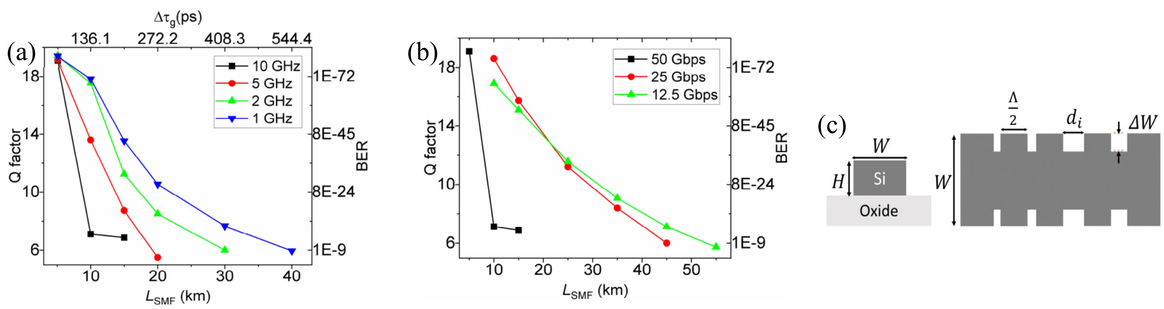

Fig. 1. (a) Calculated Q-factor vs L_{SMF} of a 50-Gbps NRZ-OOK data signal after SOD compensation using discrete phase filters with varying ν_r. The equivalent $\Delta\tau_g$ is noted in the top axis. (b) Variation of Q-factor vs L_{SMF} after SOD compensation of a NRZ-OOK signal with different bit rates, using a discrete phase filter with ν_r = 10 GHz. (c) Schematic of the phase-modulated WBG structure used for the realisation of the discrete phase filter: W, H are the waveguide width and height respectively, Λ is the nominal grating period, ΔW is the corrugation depth, d_i is the distance between successive corrugations.

The resulting phase filters are implemented using a SOI WBG, scheme in Fig. 1(c). Specifically, we consider here a design aimed at achieving SOD compensation of a 24-Gbps NRZ-OOK data signal after propagation through a 31.12 km long section of SMF. Toward this aim, we assume an 8^{th}-order super Gaussian function with peak reflectivity of 0.9 and 3-dB BW of 100 GHz as the target amplitude spectral response of the dispersive phase filter. The target filter's spectral phase response is shown in Fig. 2(a). The optical spectrum of the input data signal is also depicted on the same plot. An inverse layer peeling algorithm is used to calculate the WBG coupling coefficient (κ) profile required to achieve the target spectral response from the grating (operated in reflection), and it is shown in Fig. 2(b). We propose using a phase-modulated grating structure that can be designed to provide the desired spectral transfer function, leading to a feasible grating device. Briefly, the target apodization is achieved by incorporating a slowly varying sinusoidal phase component, $\phi_{AP}(z)$, in the phase function of the WBG, shown in Fig. 2(c). Specifically, the effective index profile of the WBG, $n(\lambda, z)$, as a function of wavelength λ and device length z can be expressed as:

$$n(\lambda, z) = n_{eff}(\lambda) + \Delta n \cdot cos\left\{\frac{2\pi}{\Lambda}z + \phi(z) + \phi_{AP}(z)\right\} \quad (3)$$

where Δn is the constant grating strength, Λ is the nominal grating period, and $\phi(z)$ is the grating phase. A detailed description of the involved design process is provided in ref. [5]. A multimode waveguide with W = 2 µm and H = 220 nm is chosen to implement the phase filters, owing to their lower sensitivity to phase noise and sidewall roughness. Λ is designed to be 278 nm for a 1550-nm center wavelength operation. ΔW is set to 100 nm. The total length of the designed WBG is ~4.1 mm. A transfer matrix method is used to calculate the resultant WBG's complex spectral response. Fig. 2(d) shows the reflectivity (left) and phase response (right) of the designed WBG, in good agreement with the target response (dotted). For the same design parameters (namely net dispersion and BW), a LCWBG would require to be at least ~ 2.1 cm long (at least 5× longer device length), making it very challenging for realization in a SOI platform, such as the one used here.

Based on the optimized parameters discussed above, a GDS layout was designed consisting of input/output grating couplers (GCs), a Y-splitter, linear adiabatic tapers, an adiabatic linear terminator, and the designed WBG [4]. GCs

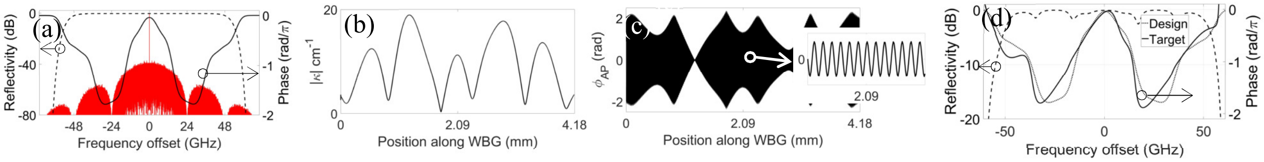

Fig. 2. (a) Spectrum of the input 24-Gbps NRZ-OOK data signal (red) and target reflectivity (left), and spectral phase profile (right) of the WBG. Notice how the spectral phase profile is bounded to 2pi, which is the key to shorten the device length (b) Coupling coefficient (κ) profile extracted from an inverse layer peeling algorithm. (c) Variation of ϕ_{AP} along the WBG's length. Inset shows a zoom of the sinusoidal variation. (d) Calculated reflectivity (left) and associated spectral phase response (right) of the WBG.

were designed to launch a transverse electric (TE)-like optical mode inside the WBG. A 20-µm long linear adiabatic taper connects the input single mode waveguide ($W = 0.5$ µm) with the 2-µm wide multimode waveguide. The Y-splitter was used to collect the reflected signal from the WBG. The designed layout was fabricated by Applied Nanotools. Firstly, the full complex spectral response of the WBG was measured using an optical vector analyzer (see Fig. 3(a)). The spectral phase profile along the filter's passband matches closely the target spectral phase response. Fabry–Perot like oscillations in the measured amplitude response are mainly attributed to end-facet reflections. A block diagram of the experimental setup is shown in Fig. 3(b). A 24 GSa/s arbitrary waveform generator (AWG) was used to drive a 40-GHz intensity modulator (IM) to generate the 2^{15}-1 PRBS NRZ-OOK signal. Next, a 31.12 km spool of standard SMF was used to optically disperse the data signal. After amplification, the dispersed signal was coupled to the on-chip phase filter using GCs. The resultant signal was amplified and measured using a 500-GHz optical sampling oscilloscope (OSO). Optical amplification is required due to the higher coupling loss (~10 dB). Alternatively, edge-couplers could be used to reduce the coupling loss below 3 dB. Fig. 3 (c, d) shows the measured eye diagrams of the data signals with different bit rates (from 12 to 24 Gbps) (c) after dispersive propagation and (d) after reflection from the WBG phase filter. Eye diagrams were measured at a constant average power of ~ 8 dBm. As observed in Fig. 3(e), the phase filter provides the desired dispersion compensation even when the data signal is completely distorted (Q-factor ~ 0, corresponding to a fully closed eye diagram) due to dispersion-induced inter-symbol interference (ISI).

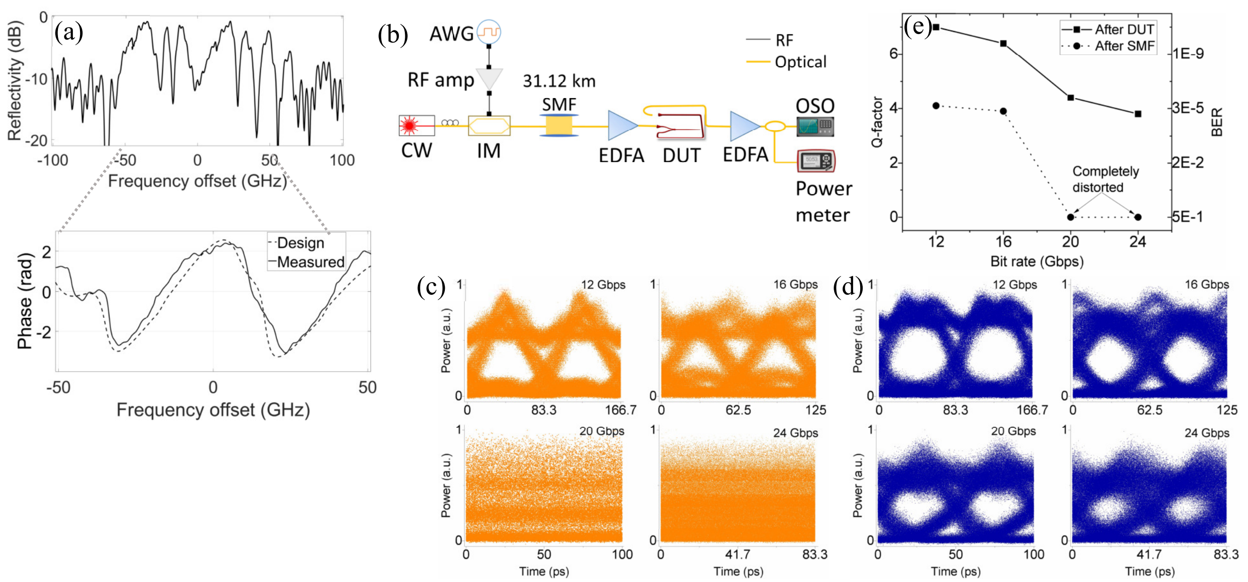

Fig. 3. (a) Measured reflectivity (top) & measured vs. designed phase response along the filter's passband (bottom) (b) Experimental setup: EDFA – Erbium-doped fiber amplifier, DUT – device under test (SOI WBG phase filter). (c, d) Measured eye diagrams for different bit rates after dispersive propagation through 31.12 km of SMF (orange) (c), and after reflection from the DUT (blue) (d). (e) Measured Q-factor and BER versus input bit rate: after dispersive propagation (dotted) and after reflection from the DUT (solid).

We highlight that the proposed solution can be easily extended to other low-loss on-chip platforms, such as silicon nitride, etc. This should allow the realization of devices with frequency resolution narrower than 1 GHz, further extending the range of GVD values that could be compensated for. Future work will investigate the potential of the proposed solution for application on advanced modulation formats.

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