Passive Amplification of Data Signals using On-chip Dispersive Phase Filters in Silicon

Saket Kaushal(1)*, Charalambos Klitis(2), Marc Sorel(2), and José Azaña(1)

(1) Institut National de la Recherche Scientifique – Centre Énergie Matériaux Télécommunications (INRS-EMT) 800, de La Gauchetière Ouest, Montréal H5A 1K6 Canada, *saket.kaushal@emt.inrs.ca

(2) School of Engineering, University of Glasgow, Glasgow G12 8LT UK

Abstract We propose a dispersive phase filter design for passive amplification of data signals using waveguide Bragg gratings in silicon. In experiments, passive amplification by a factor ~ 3 of a PAM-4 data signal is demonstrated using this design.

Introduction

The process of phase modulation of continuous wave (CW) light followed by dispersive propagation through a dispersive delay line, e.g., chirped fiber Bragg grating (CFBG), is a well-studied method of pulse compression and generation [1,2]. This technique has been further extended to achieve passive amplification of arbitrary optical waveforms, such as telecom data signals [3]. Higher passive gain factors have been achieved using an alternative temporal Talbot array illuminator design [4]. Passive amplification is inherently noiseless, providing important noise mitigation capabilities [4]. However, all these processes require a large amount of group velocity dispersion (typically > 300 ps/nm) over a broad bandwidth (BW), which is extremely challenging to realize in on-chip integrated platforms. Nevertheless, it is well understood that temporal phase modulation of CW light creates discrete frequency components at integral multiples of the modulation frequency [1]. Thus, we anticipate that full spectral phase accumulation (as induced by dispersion) could then be effectively replaced by a line-by-line spectral phase filtering operation wherein individual phase excursions can be designed to be within the $[0,2\pi)$ range. This potentially leads to considerably shorter device lengths and opens the door for on-chip integration [5]. In this communication, we discuss the general design principle to realize dispersive phase filters based on this concept using waveguide Bragg gratings (WBGs), and provide the specific design guidelines for the target application (passive amplification of arbitrary waveforms). In experiments, we demonstrate, for the first time, passive amplification by a factor of ~ 3 of a PAM-4 data signal at a sampling frequency of 20 GHz, using mm-long dispersive phase filters in a silicon-on-insulator (SOI) platform.

Design Principle

Let us first consider a compact optical pulse generator, in which CW light is phase modulated by an RF sinusoid in an electro-optic phase modulator (PM) and subsequently compressed into pulses by a second-order dispersive medium, e.g., a CFBG, with net group-velocity dispersion (GVD) B_2. For a given modulation frequency (f_m) and modulation index ($\Delta\theta$), there exists a minimum value of net GVD (B_2^0), which provides maximum compression/peak power of the resultant pulses and is given by the following empirical relation [1], valid for $1 < \Delta\theta < 10\,rad$:

$$B_2^0 \approx \frac{1}{f_m^2(30.45 \cdot \Delta\theta - 12.56)} \qquad (1)$$

The generated optical pulses repeat at a rate determined by the modulation frequency f_m. Moreover, if we simply vary the net GVD and record the corresponding amplification factor (ratio of peak power to average power) of the resultant output pulses, we observe that in addition to B_2^0, there exist multiple values of net GVD $(B_2^s), s = 0, 1, 2, 3 \ldots$ that provide amplification by the same factor, as shown in Fig. 1.

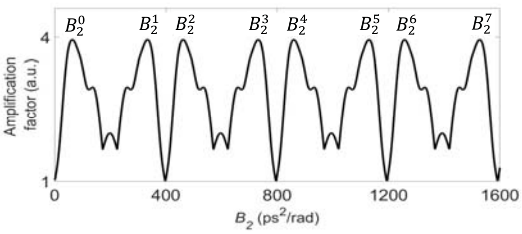

Fig 1: Variation of amplification factor of the output pulses as a function of net GVD (B_2) for $\Delta\theta = \frac{\pi}{2}$ and $f_m = 20$ GHz

Using a bi-variate analysis, we determined a closed-form empirical expression for B_2^s values:

$$B_2^1 \approx -\frac{4.116 \cdot 10^{-2}}{f_m^2}\Delta\theta^{-1.051} + \Delta B_2$$

$$B_2^{2s+1} = B_2^{2s-1} + \Delta B_2$$

$$B_2^{2s} = B_2^{2(s-1)} + \Delta B_2$$

$$\Delta B_2 = \frac{1}{2\pi f_m^2}$$

This analysis provides an important additional degree of flexibility in the selection of a medium with appropriate GVD for the target operation.

The described scheme for optical pulse generation from CW light (PM + dispersion) can be utilized to achieve undistorted passive amplification of an incoming arbitrary optical signal provided that $f_m > \Delta f_i$, where Δf_i is the full BW of the input signal (Nyquist criterion). Consider a simple case to realize passive amplification of a 2.4-Gbaud/s PAM-4 data signal (see Fig. 2(b)). Assuming, $f_m = 20\ GHz$ and $\Delta\theta = \pi/2$, the required $B_2^0 \approx 70$ ps^2/rad for amplification by a factor of ~ 4. For the on-chip phase filter design reported herein, we have considered another value of B_2 i.e., $B_2^2 \approx 470$ ps^2/rad. Since, the phase-modulation process creates discrete frequency components at integral multiples of f_m, an equivalent phase filter can then be designed to replace the quadratic spectral phase imposed by a conventional GVD medium (e.g., a CFBG) through the use of a line-by-line spectral phase filtering operation having a *spectral resolution* f_m (see Fig. 2(a)). For the aforementioned case, the required spectral phase response of the filter is shown in Fig 2(c). The individual phase excursions are wrapped within the $[0,2\pi)$ range. The spectrum of the phase-conditioned data signal is also presented to illustrate the discrete spectral phase filtering operation. After undergoing this operation, the input signal energy is focused onto consecutive short pulses, spaced by $1/f_m$, which follow a temporal envelope that underlines an amplified copy of the input signal, with an estimated passive amplification factor (mean ratio of the output to the input signal power along the time domain) of ~ 4, as shown in Fig. 2(d).

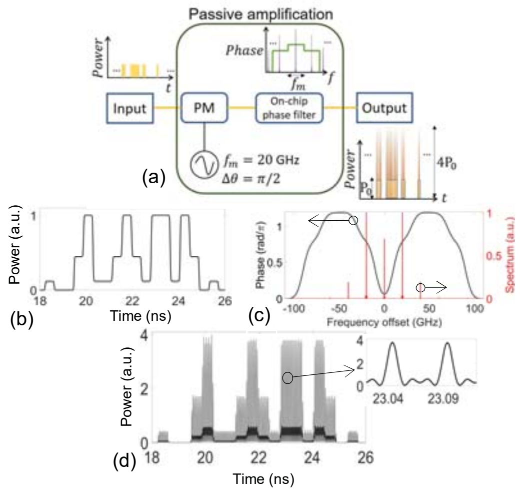

Fig. 2 (a) Schematic of the passive amplification process using a PM and on-chip dispesive phase filter (b) Input 2.4-Gbaud/s PAM-4 signal. (c) Calculated spectral phase response of the phase filter, and the spectrum of the phase-conditioned PAM-4 data signal. (d) Calculated output temporal waveform normalized with respect to the peak of the input signal, inset shows the individual pulses at repetition rate of 50 ps

Toward this aim, we target a dispersive phase filter with an amplitude spectral response that follows an 8^{th}-order super Gaussian function with peak reflectivity of 0.5 and 3-dB BW of 500 GHz, here implemented using a WBG. The target filter's spectral phase response is shown in Fig. 3(b). An inverse layer peeling algorithm is used to calculate the coupling coefficient (κ) profile required to achieve such a response, result shown in Fig. 3(c). We propose using a phase-modulated grating structure that can be practically designed to provide the desired spectral transfer function [6].

Briefly, the target apodization is achieved by incorporating a slowly varying sinusoidal phase component in the phase function of the WBG (schematically drawn in Fig. 3(a)) as shown by $\phi_{AP}(z)$ in Eq. 2:

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

Here $n(\lambda, z)$ is the effective index profile of the WBG as a function of wavelength λ and device length z, Δn is the constant grating strength (achieved by employing a small and constant grating recess amplitude, ΔW), Λ is the nominal grating period, $\phi(z)$ is the grating phase (or phase of the target coupling coefficient) and $\phi_{AP}(z) = \phi_0(z).\sin\{(2\pi/\lambda_P)z\}$ is the apodization phase function having a slowly modulating amplitude $\phi_0(z)$ and phase period Λ_P. $\phi_0(z)$ is mapped to the normalized target apodization profile, $f(z) = |\kappa(z)|/\kappa_{max}$, through a 0^{th}-order Bessel function namely, $\phi_0(z) = J_0^{-1}(f(z))$. In this design, Λ_P is selected such that the additional reflection sidebands created through the phase modulation process fall outside the spectral region of interest. Λ_P is fixed at 3 μm. The grating phase components $\phi(z)$ and $\phi_{AP}(z)$ can be physically implemented by modulating the distances (d_i) between the i^{th} and $(i+1)^{th}$ corrugation along the WBG [7]. A 500 nm wide × 220 nm thick single mode waveguide in a SOI wafer is chosen to implement the phase filters. Λ is set to 324 nm for a 1550-nm center wavelength operation. ΔW is fixed to 5 nm. The total length of the WBG is ~ 1.6 mm. A transfer matrix method (TMM) is used to calculate the WBG's complex spectral response [8]. Fig. 3(d) shows the variation of ϕ_{AP} along the WBG. Fig. 3(e) shows the calculated reflectivity (left) and phase response (right) of the designed WBG, in good agreement with the target response (Fig. 3(b)). For comparison, we estimate that a linearly chirped WBG (LCWBG) would require to be at least twice longer than the phase filter designed herein, i.e., with a device length of ~ 3.2 mm, to provide a net GVD $B_2^0 \approx$ 70 ps^2/rad over a 200-GHz BW. The device length of a LCWBG scales proportionally with BW and net GVD (B_2), whereas the device length of an on-chip dispersive phase filter remains nearly independent of BW and B_2, though it depends on f_m [5].

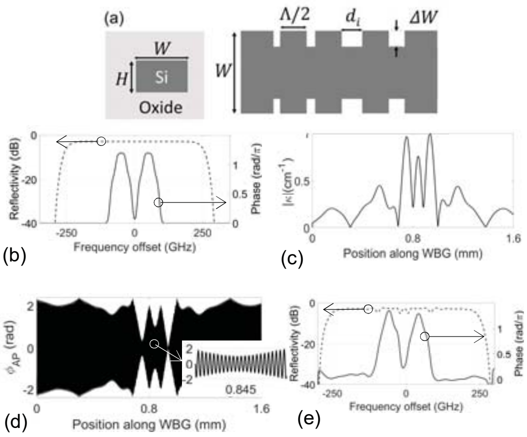

Fig. 3 (a) Schematic of the phase modulated WBG: H is the waveguide height, W is the waveguide width, ΔW is the corrugation width, Λ is the nominal grating period and d_i is the distance between successive corrugations. (b) Target reflectivity (left) and, spectral phase profile (right) of the WBG. (c) Coupling coefficient (κ) profile extracted from an inverse layer peeling algorithm. (d) Variation of ϕ_{AP} along the WBG's length. Inset shows a zoom of the sinusoidal variation. (e) Calculated reflectivity (left) and associated spectral phase response (right) of the designed WBG.

Experimental results

The designed WBG was fabricated using electron beam lithography and inductively coupled reactive ion etching at University of Glasgow. Firstly, the full complex spectral response of the WBG was measured using an optical vector analyzer (see Fig. 4(a,b)). The central wavelength of the filter was shifted to ~ 1568 nm, due to fabrication imperfections. Fabry–Perot like oscillations in the measured amplitude response are due to end-facet reflections. The measured spectral phase response along the filter's passband matches closely the designed phase profile, as seen in Fig. 4(c). The experimental setup used for proof-of-concept demonstrations of the proposed passive amplification process follows the schematic depicted in Fig. 4(d). The input 2.4-Gbaud/s PAM-4 signal was generated using a CW laser and an intensity modulator (IM), driven by an arbitrary waveform generator (AWG). Subsequently, the generated signal was phase modulated using a PM, driven by a 20 GHz radio frequency source (RFS). After amplification through an Erbium-doped fibre amplifier (EDFA), the phase-conditioned data signal was coupled to the on-chip dispersive phase filter using grating couplers. The resultant signal was amplified and subsequently detected using a high speed photodetector (3-dB detection BW 50-GHz), attached to a 50-GHz electrical sampling oscilloscope (ESO). Fig. 4(e) shows the measured spectrum of the phase-conditioned data signal. Fig. 4(f,g) show the measured temporal waveforms when the PM is turned OFF (input signal attenuated by the insertion losses of the processing system) and ON (output signal), respectively. The output waveform is clearly proportional to the input signal with an intensity 2.8× compared to the PM OFF case, in close agreement with the theoretical predictions (intensity 3.3×), considering the practical detection bandwidth limitations.

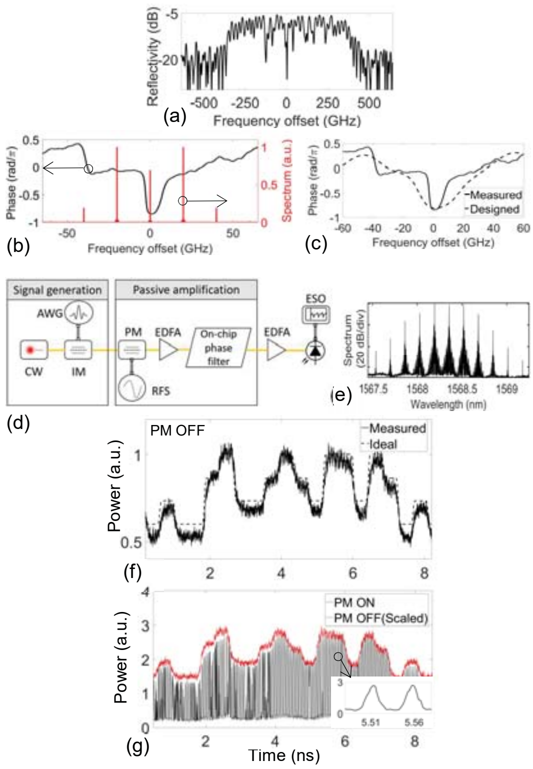

Fig. 4 (a) Measured reflectivity of the WBG (b) Phase response along the filter's passband (left axis) and the spectrum of the input phase-conditioned data signal (right axis, red curve). (c) Measured phase response (black) and designed phase response (red) of the phase filter. (d) Schematic of the experimental setup, with the acronyms defined in the text. (e) Measured spectrum of the phase-conditioned data signal (f,g) Measured temporal waveforms when the PM is turned OFF and ON respectively, normalized with respect to the peak of the PM-OFF signal. Inset shows a detail of the individual pulses, at repetition rate of 50 ps.

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