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Optimum Phase Control for Parametric Spectral Shaping

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Abstract: For the first time, we demonstrated by numerical simulations that parametric spectral shaping is feasible by phase control of individual phase-locked lines. Its effectiveness is demonstrated for flattening of a soliton-shape optical frequency comb. © 2025 The Author(s)

1. Introduction

Optical frequency combs are highly versatile tools that find applications in spectroscopy, astronomy, sensing, time-transfer, and communication [1]. They can be generated using mode-locked lasers, micro-ring resonators, electro-optic modulation, supercontinuum generation, etc. [1]. For many applications, control of the comb spectrum is critical. In most comb generation platforms, e.g., microcombs, arbitrary control of the comb spectrum is, however, not available.

Nonlinear processes in various materials and waveguides have been used to generate and broaden frequency combs [2,3]. This paper investigates whether the parametric interaction between comb lines can be used to shape the resulting spectrum according to a particular target shape by controlling the relative phase of the input comb lines. As comb lines are phase-locked, their parametric interaction becomes phase-sensitive and dependent on the relative phases of the interacting lines.

Unlike conventional phase-sensitive amplification techniques [4] that rely on external pump sources, and prior methods using programmable filters for line-by-line adjustments of both amplitude and phase [5], this work focuses solely on redistributing power among the comb lines through phase-only manipulation. This approach simplifies the comb shaping system and avoids the substantial loss and complexity associated with amplitude filtering and pulse shaping techniques.

Finding a solution to the aforementioned problem for a large number of comb lines is, a highly complex optimization problem, due to the intricate nonlinear interaction governed by the generalized nonlinear Schrödinger equation (GNLSE). In this paper, *for the first time*, a theoretically optimal solution employing gradient-based phase control is proposed. The proposed approach relies on automatic differentiation, a widely used framework for optimization of large machine learning models, for gradient computation through the GNLSE. It is demonstrated that it is feasible to significantly flatten a soliton-shaped frequency comb by purely manipulating comb line phases to control the parametric interactions in a nonlinear waveguide. This approach could be applied to various comb shapes to enable easy and efficient control of the resultant comb shape—also beyond the sech-shaped comb investigated in this initial demonstration.

2. Methodology

The main principles of the proposed approach are illustrated in Fig. 1. The phase optimization problem is formulated as follows: determine the phase relations between the input comb lines that minimize the error between the output of the (GNLSE), describing the nonlinear interactions and the target spectrum.

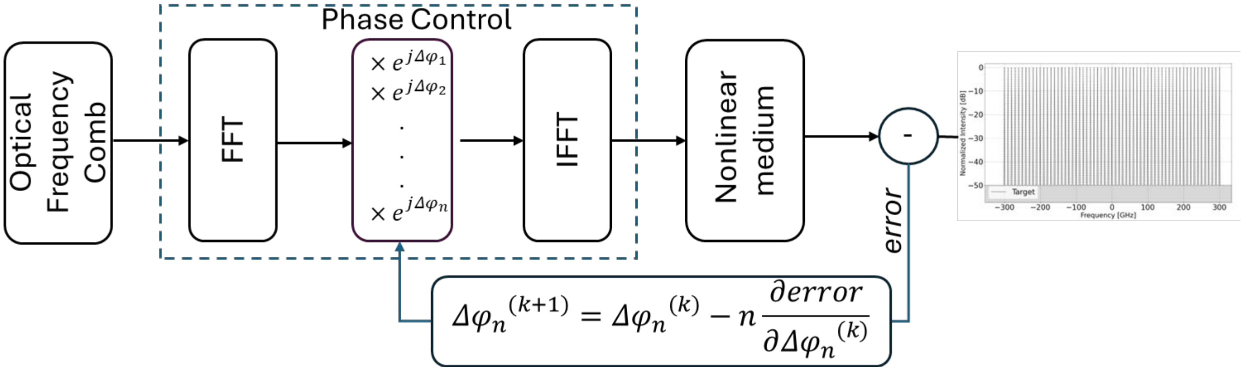

Figure 1.The proposed numerical set-up for the investigation of parametric spectral shaping.

As depicted in Fig. 1, the input comb phases are adjusted in the frequency domain and transformed back to the time domain via an inverse Fourier transform. The phase-adjusted comb is simulated propagating through a nonlinear waveguide modeled by the GNLSE with parameters corresponding to a SiN waveguide, solved numerically using the Split-Step Fourier Method (SSFM). To optimize the phases, an iterative stochastic gradient descent (SGD) [6] scheme with adaptive learning rates is employed, efficiently handling the nonlinear problem. Implementing the SSFM in a fully differentiable manner enables gradient-based optimization through automatic differentiation, allowing efficient computation of gradients with respect to the input phases within the optimization loop.

3. Numerical Results

The proposed method is applied to flatten the spectrum of a soliton-shaped frequency comb. The repetition rate is chosen to be 10 GHz and the average power is 16 dBm. For the nonlinear medium, a Highly Nonlinear Waveguide (HNLW) [7] with the following properties is used: length L=3mm, attenuation parameter α = 3 dB/cm, non-linear parameter $\gamma = 1.5 \times 10^{4}\ W^{-1}km^{-1}$ and dispersion profile of β_2=-0.64ps^2/km, β_3=2.4×$10^{-3}\ ps^3/km$, β_4=-1×$10^{-6} ps^4/km$. The target spectrum is set to be a 61-line flat comb with a bandwidth of 600 GHz. Phase optimization is performed on *N*=40 comb lines centered around the central frequency of the input frequency comb. Specifically, the control focuses on the phase differences $\Delta\varphi_n$, which represent the phase difference of each of the *N* comb lines relative to the central line.

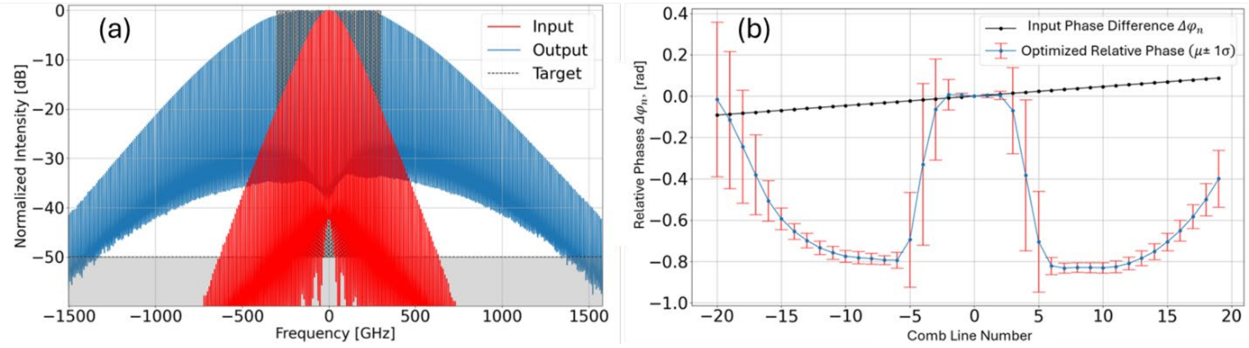

Figure 2.(a)Input spectrum (red), optimized spectrum(blue), target spectrum (shadowed gray); (b) Mean optimized phased differences per comb line

In Fig. 2(a), input and target spectra, as well as the output spectrum after the optimization are shown. It is observed that by controlling the phase difference of 40 input combs spectra lines it is possible to get an output spectra with 61 lines with flatness of 0.14 dB. To assess the optimization's robustness, Fig. 2(b) shows the mean and standard deviation of optimal phase differences from 1000 random initializations, revealing a structured pattern.

4. Conclusion

The feasibility of spectral shaping through the control of parametric interactions between comb lines has been demonstrated numerically in a nonlinear medium. By optimizing the relative phases among the input comb lines, we have successfully shown that it is possible to redistribute power and significantly flatten a sech-based frequency comb.

5. Acknowledgements

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