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Design of Optimal Dispersive Mirrors for Femtosecond Enhancement Cavities and Compressors by Minimizing Phase Distortion Power

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Abstract: The optimization of phase distortion spectral power density is proposed as an alternative to GDD minimization of ultrafast cavity mirrors. This criterion is shown to minimize the detuning of cavity resonances from a uniform comb.

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1. Introduction

Enhancement cavities for laser combs have received considerable attention recently, both in the context of maximizing nonlinear conversion through field enhancement [1], as well as for repetition rate (comb spacing) enhancement for spectroscopy [2]. In either case, a crucial aspect of such cavities is the mirror design, which must exactly compensate for intracavity dispersion (if any) such that the cavity modes remain equidistant. Typically, phase sensitive mirrors (and in fact most phase sensitive optical devices, for that matter) have been designed by seeking to minimize the spectrally integrated deviation of the group delay dispersion (GDD) from that desired. While this technique works adequately for small relative bandwidths (the domain in which the concept of GDD first arose), where a second-order series expansion of phase is valid, it does not always yield optimal results with the kinds of large relative bandwidths accessible with modern mode-locked laser systems.

To be specific, a minimum integrated GDD design is not necessarily optimal when the phase has oscillations on a scale smaller than the bandwidth, corresponding to light dispersed well away from the main reflected pulse. As shown by Steinmeyer in [3], the amplitude of such GDD oscillations is proportional to the *square* of the delay between these so-called “satellite pulses” and the main pulse. In pulse compression applications, however, the timing of the satellite pulses is irrelevant, and what matters is the power contained in them. In enhancement cavities, the only concern is the absolute shifting of individual resonances, and any oscillation of the detuning as a function of frequency is irrelevant. Optimizing for minimum GDD places a significant unwarranted penalty on designs with quickly varying phase oscillations; designs will not perform as well as they could, for a given number of layers.

In lieu of mean squared GDD, we propose a new criterion based on the energy lost to phase distortions. To that end, we introduce a new spectral parameter, which we will refer to as the phase distortion ratio (PDR):

$$\text{PDR}(\omega) \triangleq \left[\Delta\phi(\omega) - \frac{1}{\Delta\omega^2} \left\{ (\Delta\omega^2 + \omega_0^2) \langle \Delta\phi(\omega) \rangle + \omega \langle \omega \Delta\phi(\omega) \rangle - \omega_0 (\omega \langle \Delta\phi(\omega) \rangle + \langle \omega \Delta\phi(\omega) \rangle) \right\} \right]^2, \quad (1)$$

where $\Delta\omega$ is the pulse bandwidth, ω_0 the center (mean) frequency, and $\Delta\phi$ the raw computed phase error. The angle brackets denote an optical power weighted mean. Multiplying $\text{PDR}(\omega)$ by the incoming power spectral density and integrating yields the total optical power contained in phase distortions. The complexity of the expression is due to the need to take out an arbitrary constant and linear phase from the raw phase error. Having a closed form expression for the PDR (as opposed to leaving floating phase terms) allows for highly efficient numerical optimization using analytic gradients. In practice, computing the gradient of the PDR is at least 2-4 times faster than working with GDD [4]. Finally, we would like to note that while we focus here on thin film filter design, this approach has applications for any wide-bandwidth optical device.

2. Enhancement Cavity Mirror Optimization

We have already demonstrated in previous work that phase distortion power is highly effective as a merit function for designing chirped mirror compressors, resulting in mirrors that introduce significantly less broadening relative to GDD minimized stacks [5]. In this work, we show that optimal design of enhancement cavity mirrors involves minimizing phase distortion power, as well.

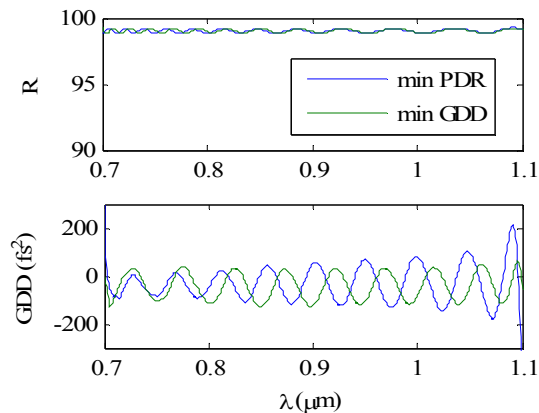


Fig. 1: Comparison of PDR and GDD optimized enhancement cavity mirrors. The PDR mirror has worse GDD performance, as expected. The reflectivity of the two designs is roughly equal.

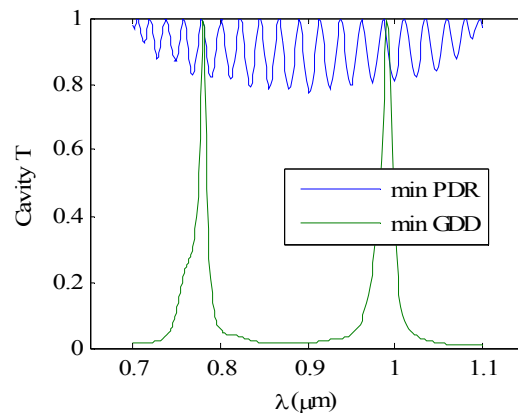


Fig. 2: Cavity transmission for both designs shown in Fig. 1. The minimum PDR design transmits over 90%, whereas the minimum GDD design only has a bandwidth of a few nanometers.

For relatively narrow relative bandwidths, less than 1/10, enhancement cavities can be designed for low dispersion by using mirrors based on Bragg stacks. To progress beyond that, however, enhancement cavities with chirped mirrors will have to be used, with intracavity positive dispersion elements introduced. Given the extreme sensitivity of wide bandwidth cavities to resonance shifts, proper design of the mirrors will be imperative to successful implementation, and the performance of the mirrors will be the limiting factor to bandwidth.

Assuming the reflectivity of the mirrors maintains a sufficient cavity Q for field enhancement and/or mode suppression, the dominant mechanism affecting the cavity throughput will be the detuning of cavity resonances due to mirror dispersion nonideality. To second-order, the spectral transmission of a comb through a locked cavity can be shown to be equal to

$$T(\omega) = 1 - Q(\omega) \text{PDR}(\omega) \quad (2)$$

An optimal design approach is thus to minimize the power weighted mean PDR of the mirror, subject to the constraint that the mirror reflectivity stays within a band such that sufficient cavity Q is maintained.

3. Results

To demonstrate the efficacy of PDR optimization of cavity mirrors, we considered the case of an ultra-broadband rate enhancement cavity with a modest Q factor of 400, created by a two identical (i.e. non complimentary) chirped mirrors. The cavity was assumed to have roughly 100 fs² of internal dispersion. Such a cavity would be useful for increasing the mode spacing of a femtosecond comb for high precision astrophysical spectroscopy, as in [2].

To begin with, a double chirped mirror was designed using the standard GDD optimization approach. This mirror was then reoptimized using the criterion in (2), starting from the minimum GDD design to be absolutely fair. These two designs are compared in Fig. 1, where it is clear that the GDD optimized design (green) has less GDD ripple than the minimum PDR design (blue), as one would expect.

The theoretical cavity transmission (assuming perfect cavity locking) is shown in Fig. 2. Despite the apparent lower dispersion ripple of the GDD optimized mirror, it is virtually useless in the cavity, admitting only a few nanometers of bandwidth before the mirrors dephase the cavity from the comb. The PDR optimized cavity, however, transmits an average of at least 90% over the entire 400 nm bandwidth. Moreover, there is significant room left for improvement in bandwidth and/or Q factor through the use of complimentary chirped mirror pairs.

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