Relationships among group delay, energy storage, and loss in dispersive dielectric mirrors

Péter Gyula Antal and Róbert Szipőcs*

Research Institute for Solid State Physics and Optics, P.O. Box 49, H-1525 Budapest, Hungary

**Corresponding author: szipoecs@sunserv.kfki.hu*

Received August 24, 2011; accepted November 22, 2011; posted online January 17, 2012

We show that absorbed and stored electromagnetic energy are proportional to the reflection group delay in highly reflective dispersive dielectric mirrors over the high-reflectivity band. Our theoretical considerations are verified by numerical simulations performed on different dielectric mirror structures. The revealed proportionality between group delay and absorbed energy sets constraint on the application of ultrabroadband and/or dispersive dielectric mirrors in broadband or widely tunable, high-power laser systems.

OCIS codes: 310.6805, 140.3330, 260.2030.

doi: 10.3788/COL201210.053101.

In the last two decades, theoretical and experimental investigations on reflection delay time of optical pulses reflected by multilayer dielectric structures have been of scientific interest because frequency-dependent group delay (GD) of the dielectric mirrors can be well suited for intracavity or extracavity dispersion compensation of ultrashort pulse lasers[1]. Aperiodic dielectric mirror structures, which are often referred to as chirped mirrors, are advantageous, not only because they introduce a certain amount of negative dispersion, but also because they exhibit a considerably broader high-reflectance band than standard, low-dispersion quarter-wave (QW) mirror stacks. Aside from chirped mirrors, there is another group of dispersive mirrors referred to as: Gires-Tournois interferometer-type mirrors[2]. The fact that a relationship exists between the electromagnetic energy stored in the volume of a thin-film structure and its GD is known in the field of telecommunication technology[3]. This relationship is also a starting point in resolving the long-haul scientific problem of superluminal delay times of electromagnetic wave packets during transmission through highly reflective, lossless photonic bandgap structures[4]. In practical laser systems, however, one usually cannot neglect the absorption (or scattering) loss of dielectric multilayer mirrors because laser performance, such as intracavity loss, beam quality, maximum output power, laser damage threshold power, and others, strongly depends on these physical quantities. From this aspect, one can address the question of whether a general relationship exists between the reflection GD and the absorption loss of a dielectric multilayer mirror (throughout the letter, we mean one-photon or linear absorption when we use the word "absorption"). For QW-stack mirrors, GD and absorptance have been shown as proportional to each other at the central wavelength of the QW mirror when the loss is sufficiently low[5]. For a specific multistack multilayer mirror design, Ferencz *et al.* also found conspicuous, but unexplained, proportionality of these two physical quantities[6]. For a nonspecific, general, highly reflective dielectric mirror structure, however, neither the relationship between GD and the absorptance nor the relationship between GD and the stored energy in the presence of loss has been investigated systematically thus far.

In this letter, we first theoretically deduce the relationship among group delay, stored energy, and absorptance of a highly reflective multilayer mirror of a general design, after which we verify our theoretical results by numerical simulations. Proportionality between the absorptance and the GD is very important for application of ultrabroadband chirped mirrors (UBCMs)[7] or highly dispersive mirrors[8] in high power, pulsed laser systems: these mirrors are used for broadband feedback and dispersion compensation, and their reflection GD is typically one or two orders of magnitude higher than that of the low-dispersion QW stacks. However, low reflection loss is crucial in case of dielectric mirrors designed for such lasers: the absorbed power of the laser beam is transformed to heat, which can lead to wavefront distortion or, worse, damage to the coating due to a linear absorption process, which is the dominating damage mechanism for >50 ps pulse durations[9]. For shorter pulses, one should also consider nonlinear processes, such as two-photon absorption or avalanche ionization, which are beyond the scope of this letter. Dielectric mirrors exhibiting relatively high GD on reflection, however, are not exclusively used in ultrashort pulse laser systems. UBCM structures[7] are widely used in broadly tunable CW or ns pulse lasers or in optical parametric oscillators and amplifiers for beam steering or feedback over a wide frequency range. In these applications, linear absorption loss, subsequent heating, and mirror damage could be critical issues. Loss in dielectric mirrors becomes higher and a more important issue as we move to shorter wavelengths, especially in the UV spectral range.

As a starting point in our theoretical investigations, we recall the main results in Ref. [4], in which the transmission of a relatively narrowband light pulse through a lossless photonic barrier was investigated. Using the continuity equation for energy, Ref. [4] analytically showed that the weighted sum of the reflection GD (τ_{gr}) and the transmission GD (τ_{gt}) is equal to the so-called dwell time (τ_{d}), which is the ratio of the stored energy (U) and the incident power (P_{i}):

$$R\tau_{\text{gr}} + T\tau_{\text{gt}} = \frac{U}{P_{\text{i}}} \equiv \tau_{\text{d}}, \qquad (1)$$

