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Spectral filtering of femtosecond laser pulses by interference filters

R. Szipöcs[1,2], A. Köházi-Kis[2], P. Apai[1], E. Finger[3], A. Euteneuer[3], M. Hofmann[3]

[1] Research Institute for Solid State Physics and Optics, P.O. Box 49, H-1525 Budapest, Hungary
[2] R&D Ultrafast Lasers Kft, Konkoly Thege 29-33, H-1121 Budapest, Hungary
[3] Fachbereich Physik, Philipps-Universität, Renthof 5, D-35032 Marburg, Germany

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Abstract. Phase properties of optical thin film interference filters are discussed from the aspect of their usage for phase-error free wavelength separation of broadband femtosecond laser pulses. It is shown that both transmissive or reflective interference filters with high contrast ratios exhibit high cubic phase shifts on transmission or reflection, respectively, causing intolerable distortion in the temporal pulse shape. We show, however, that high efficiency wavelength separation of broadband femtosecond laser pulses can be achieved by using low contrast, properly designed reflective optical interference filters directly built into the cavity of the broad spectrum, femtosecond pulse lasers or parametric oscillators. For demonstrative purposes, we implemented the idea for a Kerr-lens mode-locked Ti:sapphire laser, and obtained two-color, inherently synchronized, unchirped, femtosecond pulse outputs from a single laser oscillator.

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Broadly tunable laser systems form the basis of modern optics. In particular, Ti:sapphire-based laser systems are very convenient and powerful sources of coherent light, tunable over a broad bandwidth. The discovery of ultrafast pulse generation by self-mode-locking [1] in these systems was a breakthrough for many fields of applications. The high peak powers of ultrashort pulses are exploited in a variety of nonlinear optical techniques [2] whereas the short pulse durations are important for time-resolved spectroscopy [3]. Nonlinear optical spectroscopy profited from the possibility of tuning the emission spectrum of the pulsed lasers resonant to any optical transition in the investigated material [4].

In many spectroscopic applications, the availability of two or more pulse trains with independently tunable different spectra is a basic requirement. Typical examples are pump probe experiments on organic materials [5] and nondegenerate four-wave mixing experiments using pulse trains, either with different spectral positions [6] or with different spectral widths [7]. These techniques require a femtosecond laser system offering multiple, highly synchronized outputs with independently tunable spectra.

However, the simultaneous generation of multiple pulses with different wavelengths but controllable temporal pulse separation up to now has still required rather complicated techniques. One possibility is the extracavity manipulation of the pulses by spectral filters [7] or Fourier-transform techniques [8]. The advantage of these methods is that the jitter between the different pulses can be zero, because they all stem from the same original pulse. The main disadvantage of using high contrast spectral filters is the distortion of the temporal shape of a femtosecond laser pulse. In Fig. 1, the computed transmittance and group delay on transmission are plotted for a typical thin film realization of a Fabry-Perot-type, bandpass (transmission) interference filter. In Fig. 2, the computed reflectance and group delay on reflection is plotted for a possible thin film realization of a (reflective) notch filter. In general, we found that each realization of both types of spectral filters show a huge (positive or negative) cubic phase shift around the filters' central frequencies, distorting the temporal shape of a femtosecond laser pulse being transmitted or reflected by these filters. This physical behavior of optical interference filters can be understood on the basis of the theoretical works of Tikhonravov [9] and Verly and Dobrovolsky [10], who showed that "the phase factor will vary rapidly in all small intervals near the amplitude reflectance zeros," i.e., at around the central frequency of an interference filter. They also found that "... the physical phase exhibits a phase shift of π rad at the wavenumbers corresponding to the transmittance maxima. The deeper and narrower the passband, the sharper the shifts." In other words: the narrower and deeper the transmittance band of a filter, the higher the group delay introduced by the filter upon transmission.

For the simultaneous generation of multiple pulses with different wavelengths but controllable temporal pulse separation, several groups synchronized the outputs of two separate cavities by coupling them via a common gain medium [11–13]. In these complicated two-color lasers, the jitter between the two pulse trains can be reduced to less than 2 fs [13]. However, these complicated laser setups are very difficult to align and operate; thus, they are rarely used in ultrafast spectroscopy laboratories.

Considering all the difficulties and disadvantages listed above, we came to the following conclusion: because of