# MLD vs. Transmission Gratings for the Highest-Efficiency, Most-Compact Pulse Compressors

**T. Erdogan†**
*Plymouth Grating Laboratory, Inc., 5 Commerce Way, Carver, MA 02330*
*†Corresponding author: turan@plymouthgrating.com*

**Abstract:** Contrary to popular belief MLD gratings can be designed with a wide range of periods to provide the highest overall efficiency pulse compressors that are as compact and flexible as those based on transmission gratings.

## 1. Introduction

All-dielectric diffraction gratings are well-suited for chirped-pulse amplification (CPA) lasers with pulse lengths as short as 100's of fs and moderate bandwidths up to 10's of nm. They provide higher diffraction efficiency and laser-induced damage threshold than metallic reflection gratings, resulting in higher overall compressor efficiency and more compact compressor formats, and have extremely low absorption loss. Low loss is especially important for high-repetition-rate, high-average-power (HAP) lasers. The two primary types of all-dielectric gratings are surface-relief transmission [1] and multi-layer dielectric (MLD) reflection gratings [2]. Here we compare these two types of gratings for 1 μm laser applications (e.g., 1030 nm Yb-based systems) in terms of compressor efficiency and compactness, including practical considerations like manufacturability.

Transmission gratings may be conveniently operated at the Littrow angle of incidence, resulting in simple compressor geometries and alignment schemes. They exhibit relatively consistent diffraction efficiency as well as spectral and angular bandwidth performance over a broad range of grating periods for a given wavelength. Drawbacks of transmission gratings include difficulty in designing and achieving very high efficiency and material dispersion associated with propagation through the substrate. MLD gratings achieve the highest efficiencies with no added material dispersion, and with comparable spectral bandwidth performance to that of transmission gratings. The main shortcoming of MLD's is a generally narrow angular bandwidth with high efficiency occurring only at the Littrow angle, except for the special case of a period-to-wavelength ratio of about 0.55, associated with a Littrow angle of about 66°. This is often considered to be a significant design limitation, since these are reflection gratings, and thus require an appreciable deviation angle between the incident and diffracted beams.

In this paper we show that in contrast to conventional wisdom transmission gratings can achieve very high efficiencies, and MLD gratings can be used with a very wide range of grating periods, allowing both types of gratings to yield extremely high-efficiency and compact compressor designs using even a single grating. However, because high-efficiency MLD's are significantly more manufacturable than transmission gratings, MLD's are a better practical choice for most applications.

## 2. Design Considerations

In an MLD grating there are only two places the light can go – into the $-1^{st}$ diffracted order or into the $0^{th}$ order (specular reflection). The distribution of light between these two is primarily controlled by interference associated with the thin film layers, which can be manufactured with high accuracy. Tolerances on the depth, duty cycle, and shape of the grating teeth are reasonable. In a transmission grating there are four places the light can go – the $-1^{st}$ and $0^{th}$ orders in both transmission and reflection – and the distribution is entirely controlled by the grating tooth parameters, resulting in tight tolerances on these. Unless the grating tooth region is specially designed to act as an anti-reflection (AR) coating to eliminate the reflected orders, the maximum $-1^{st}$ order efficiency for a simple binary tooth design is limited to the low 90's % range for high-dispersion gratings [1]. AR performance can be built in using large tapers in the grating teeth [1], by incorporating explicit thin-film layers above or below the grating [3], or by using a combination of high- and low-index materials in the teeth [4]. Large, controlled tapers are difficult to realize in practical etching processes, and, as shown below, incorporation of additional materials can greatly tighten the tolerances on depth and duty cycle.

Generally MLD reflection gratings are used in only the in-plane (IP) configuration, where both the incident and diffracted beams lie in the grating plane. This requires a broad angular bandwidth, and thus gratings with a period-to-wavelength ratio of about 0.55. For 1030 nm laser systems, only gratings with groove densities of about 1760 lines/mm are possible. However, MLD gratings may also be operated in the out-of-plane (OOP) configuration, with only a small impact on diffraction efficiency [5]. Using the OOP geometry, a much wider range of groove densities are possible for MLD gratings, greatly increasing flexibility and possibilities for optimizing compressor designs.

## 3. Examples

Consider a 1030 nm Yb-based laser system designed for a 500 fs gaussian pulse and a bandwidth of about 3 nm. Assume the beam is 1 cm in diameter, the pulse is stretched to 100 ps, and should be compressed in a compact, single-grating compressor with the highest possible efficiency. Typically such systems use 1700 – 1760 lines/mm gratings, and thus we could compare transmission grating solutions to an in-plane MLD solution. However, to illustrate the flexibility of the OOP MLD solution, here we assume 1600 lines/mm gratings.

Fig. 1 (left) shows the diffraction efficiencies for three optimized grating designs. A simple binary transmission grating achieves just over 94% efficiency. An even more optimal design incorporating a high-index layer in the grating teeth (following [4]) achieves 98.5%. An MLD design operated in-plane at the Littrow angle could achieve nearly 100% efficiency. The MLD design shown on the graph is at the Littrow angle but out-of-plane, with an 8° full angle of deviation between incident and diffracted beams.

Fig. 1 (right) shows the overall compressor efficiency based on a simple calculation of the averages over 3 nm and 20 nm bandwidths of the values of the single-grating curves from Fig. 1 (left) raised to the 4th power (because there are four encounters with the grating in the compressor). The multilayer Tx grating and MLD grating designs exhibit comparable efficiencies. The graph also shows the manufacturing tolerance for each design, equal to the range of depth (normalized to the design depth) times the range of duty cycle over which the design achieves the stated diffraction efficiency. The higher the tolerance, the more manufacturable the design. The target value of 0.02 is shown for reference and is based on 10% ranges. Clearly the MLD grating design is much more manufacturable.

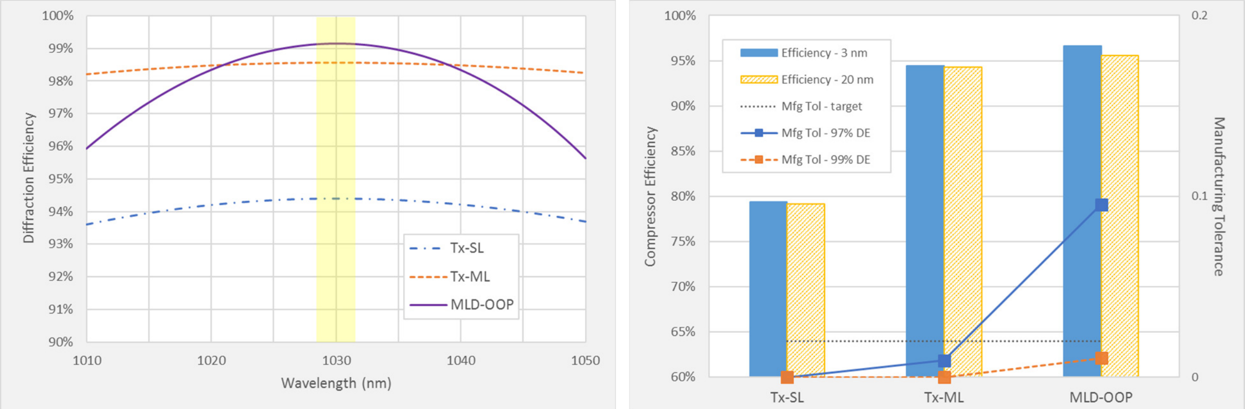

**Figure 1**. (left) Diffraction efficiencies for simple binary (Tx-SL) and multilayer (Tx-ML) transmission gratings, and an 8° deviation, out-of-plane MLD grating (MLD-OOP). (right) Overall compressor efficiencies and manufacturing tolerances associated with each grating.

Fig. 2 shows ray diagrams of compressors based on a single grating; light sees each grating four times. In both cases the gratings are 70 mm long and 30 mm wide. Ignoring mounts, the minimum compressor volume is 730 $\text{cm}^3$ for the transmission grating compressor (left) and 1030 $\text{cm}^3$ for the MLD grating compressor (right). Note the triple-roof-mirror assembly required for the OOP MLD compressor to eliminate lateral spatial dispersion.

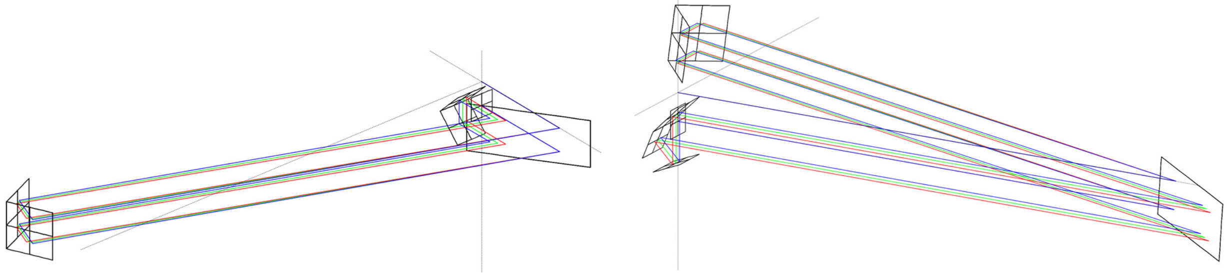

**Figure 2.** Examples of 33.3 ps/nm compressor designs based on a single transmission grating (left) and a single out-of-plane MLD grating (right). Blue, green, and red rays correspond to 1028.5, 1030, and 1031.5 nm, respectively.

[1] F. Koch, D. Lehr, O. Schönbrodt, T. Glaser, R. Fechner, F. Frost, "Manufacturing of highly dispersive, high-efficiency transmission gratings by laser interference lithography and dry etching," Microelectron. Eng. **191**, 60-65 (2018).
[2] J.A. Britten, W.A. Molander, A.K. Komashko, C.P. Barty, "Multilayer dielectric gratings for petawatt-class laser systems," Proc. SPIE 5273 (2004).
[3] K. Nagashima, A. Kosuge, Y. Ochi, M. Tanaka, "Improvement of diffraction efficiency of dielectric transmission gratings using anti-reflection coatings," Opt. Express. **21**, 18640-18645 (2013).
[4] H. Rathgen and H. L. Offerhaus, "Large bandwidth, highly efficient optical gratings through high index materials," Opt. Express. **17**, 4268-4283 (2009).
[5] D.A. Alessi, H.T. Nguyen, J.A. Britten, P.A. Rosso, C. Haefner, "Low-dispersion low-loss dielectric gratings for efficient ultrafast laser pulse compression at high average powers," Opt. and Laser Tech. **117**, 239-243 (2019).