Rapid Prototyping of Ultrafast Mirrors

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Pulsed lasers operating in the sub-100 femtosecond regime require precise optical coatings with special considerations for both group delay dispersion control and laser damage threshold. This paper outlines Optimax's rapid prototyping capabilities in designing and producing optical coatings to support the ultrafast market.

Introduction

Since the advent of chirped pulse amplification, the continued reduction in laser pulse width has opened application opportunities and created new challenges for optical coating performance. Ultrashort pulse durations and extremely high peak powers push materials into the non-linear regime, impacting absorption and laser damage threshold.[1]

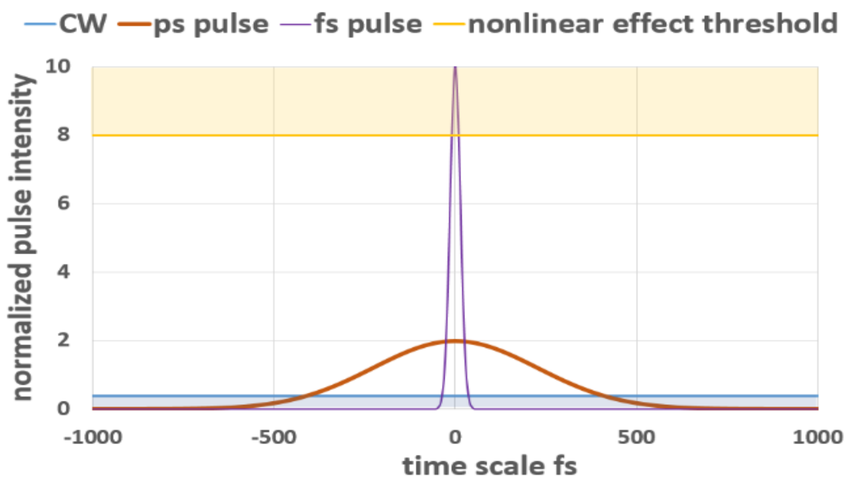

Figure1. Assuming the same energy over ±1000 fs span, the peak intensities are compared for continuous wave (CW), picosecond, and femtosecond pulse widths. The yellow shadow area represents the nonlinear zone. Only fs scale pulses break through the nonlinear threshold.

Once the peak powers exceed the nonlinear threshold, multi-photon absorption, tunnel ionization, plasma avalanche, self-focusing, and refractive index changes can occur. On the positive side, these phenomena open the door to new applications such as multi-photon microscopes, advanced waveguides, high-precision surface finishing, and micro-machining. On the negative side, peak powers are high enough to damage materials in the optical train. Thus, the first challenge with optical coatings in the femtosecond regime is laser damage. Figure 2 shows the relationship between material bandgap and the breakdown threshold of materials. Laser damage in the femtosecond regime is largely material-limited and requires materials science expertise and strict process control to achieve the best results.

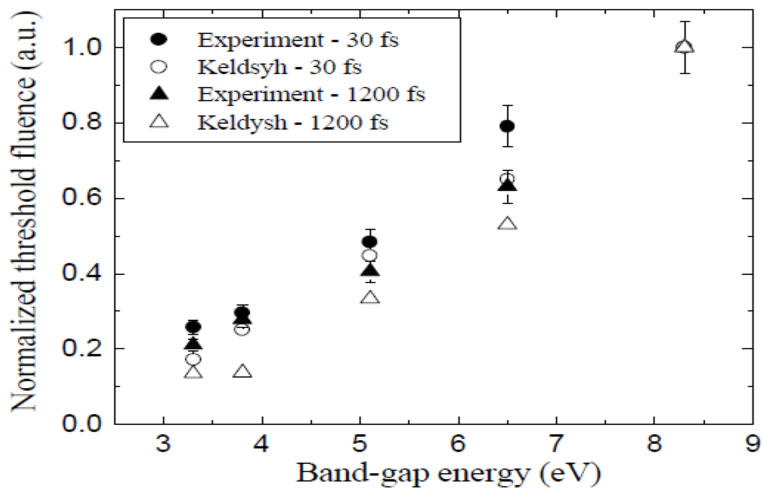

Figure 2. Normalized breakdown threshold presents a linear relation with material band-gap.[2]

The second challenge with optical coatings in the femtosecond regime is related to pulse shape control. Dispersion and the associated time delays of light moving through a material cause temporal changes in the pulse (stretching or compressing). Group delay dispersion (GDD) is a key design consideration for ultrafast coatings and describes the variation experienced by different spectral components of an optical pulse as it propagates through a medium or an optical system. Mirrors are often preferred in ultrafast optical systems because they avoid accumulated GDD through bulk materials, creating opportunities for pulse shaping and control within the coating stack by optical interference.

Rapid Prototyping

Optimax Systems, Inc. has a long history of thin film coatings for high-energy laser applications and is one of the largest global suppliers of challenging optics for the inertial confinement fusion, laser weapons, and semiconductor industries. Optimax's coating facilities, processes, and materials knowledge have continuously improved over the last twenty years to meet the increasingly challenging laser damage considerations of modern high energy laser applications. Optimax also has a long heritage of being the fastest in the market for prototyping precision optics. Combining its rapid prototyping production control systems and world-class coating capabilities allows for the rapid production of custom prototype ultrafast mirrors.

All Optimax coating and high energy laser optic packaging operations are performed in a cleanroom. Optics are cleaned before coating and shipping in ISO5 clean rooms under ISO6 benches. Ultrafast mirror coatings are produced using Ion Beam Sputtering (IBS). IBS has the precision required for adequate GDD control and typically produces the highest laser damage thresholds for sub-picosecond mirrors. The Optimax IBS machines are some of the largest in the world and can coat mirrors with up to 500 mm apertures. Internally developed models enable world-class film uniformity control in large machines, enabling low defect counts and large batch sizes in manufacturing.

Group Delay Dispersion Control

Equation (1) is the formula for pulse width elongation due to GDD

$$\tau_{out} = \sqrt{(\tau_{in}^2 + \frac{16*(Ln2)^2*GDD^2}{\tau_{in}^2})} \quad (1)$$

When net GDD is 0 fs^2, $\tau_{out}=\tau_{in}$ and the pulse width is maintained.

The following section highlights some examples of mirrors manufactured at Optimax that enable successful pulse width control.

Optimax has developed low GDD mirrors for both single-channel and dual-channel applications. Figures 3a and 3b show examples of these mirrors, both design and measured performance.

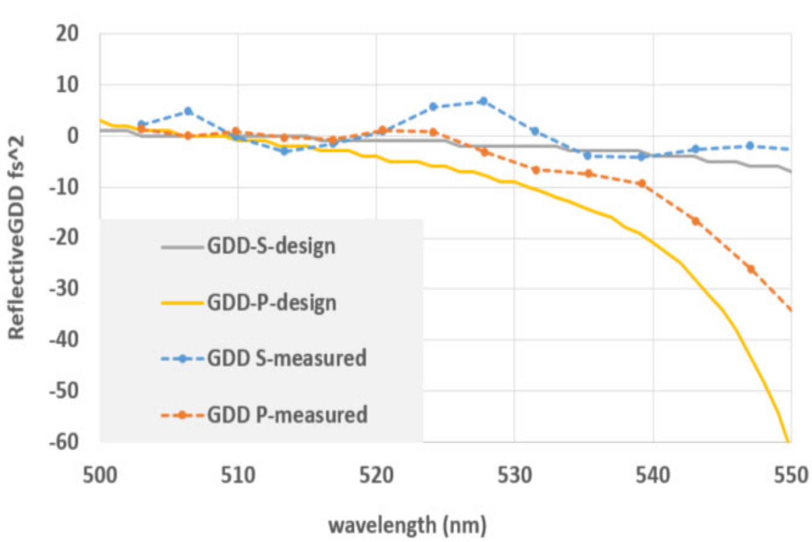

Figure 3a. Measured versus theoretical performance of an Optimax single channel low GDD mirror at 515 nm 45° (reflectivity > 99.9%).

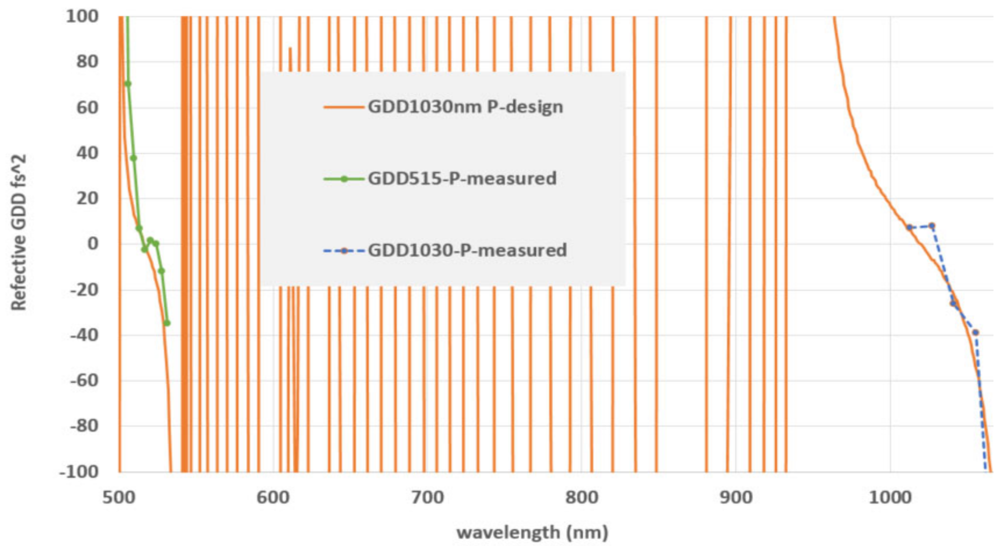

Figure 3b. Measured versus theoretical performance of an Optimax dual channel (515 nm & 1030 nm) low GDD mirror at 45° P-pol (reflectivity > 99.9%).

When the ultrafast pulse width is less than 100 fs, the pulse spectrum bandwidth noticeably increases according to Fourier transformation. Femtosecond optical frequency comb and few-cycle laser pulse are the typical cases of pulses with broad spectrum bandwidth. To accommodate this, a chirped broadband (octave span) mirror with low averaged GDD was developed, Fig 4a. A typical scenario involves a pair of octave-spanning chirped mirrors with opposite GDD ripple compensating for each other, Fig 4b.

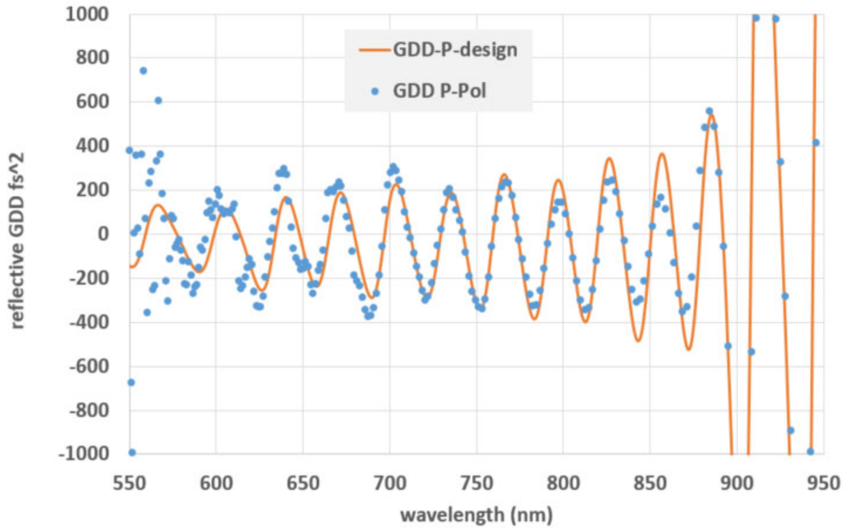

Figure 4a. **Measured versus theoretical performance of an Optimax chirped octave span broadband mirror (reflectivity > 99.5%).**

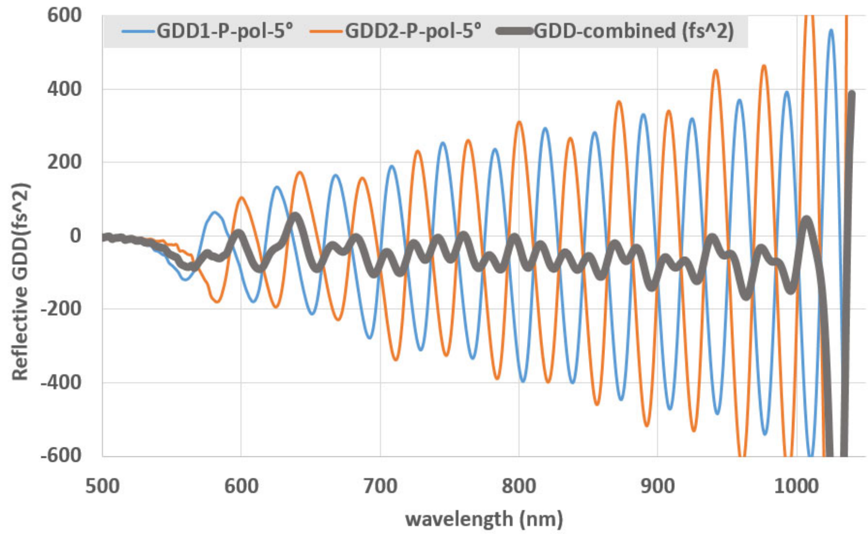

Figure 4b. Design of a chirped octave span broadband mirror pair with very low combined GDD (reflectivity for each mirror > 99.5%).

If the ultrafast pulse has already been elongated in transport through a medium, the pulse shape can be reclaimed using a compensating mirror with opposite GDD. For this, Optimax has developed negative GDD and positive GDD broadband mirrors, Fig 5.

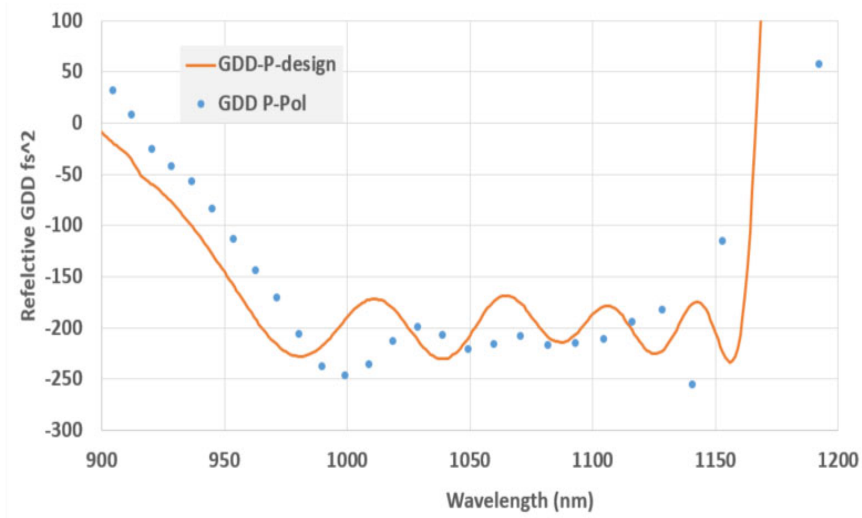

Figure 5a. Measured versus theoretical performance of an Optimax -200 fs^2 broadband mirror for positive dispersion compensation (reflectivity > 99.9%).

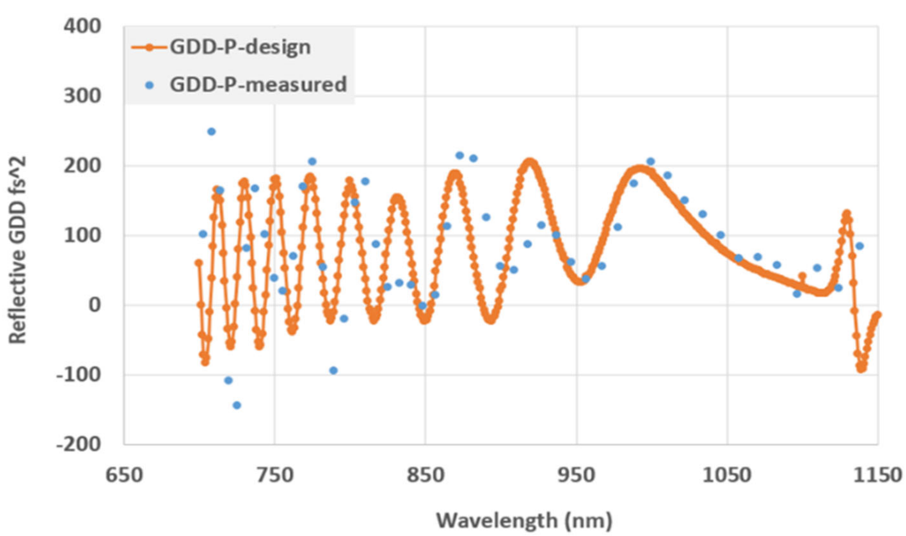

Figure 5b. Measured versus theoretical performance of an Optimax +100 fs^2 averaged GDD broadband mirror for negative dispersion compensation (reflectivity > 99.5%).

In some cases, such as Ytterbium-based laser GDD management, a highly negative GDD is required over a narrow bandwidth. Gires-Tournois-Interferometer (GTI) mirror designs are a good choice for this. This type of mirror has a large negative GDD, one which really challenges the process accuracy of thin film deposition. Optimax successfully developed a -2000 fs^2 GTI mirror, as shown in Figure 6.

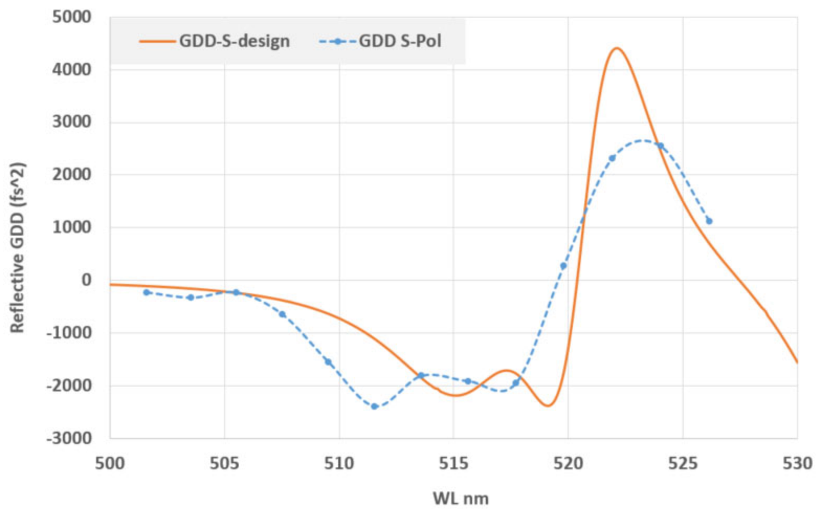

Figure 6. Measured versus theoretical performance of an Optimax -2000 fs^2 GTI mirror at 515 nm (reflectivity > 99.9%).

Laser Damage Performance

The primary means of improving the ultrafast laser damage threshold in optical coatings are material bandgap and electric field intensity related. For ultrafast mirrors, there is no reliable way to scale the laser-induced damage threshold (LIDT) between different wavelengths or pulse widths due to the complications of nonlinear effects. Repetition rates also affect the LIDT. A rough estimate is that a one-order-of-magnitude increase in the repetition rate leads to approximately a 25% decrease in the LIDT, although this relationship breaks down in the GHz region.[3] When ultrashort pulses are < 100 fs, it is noticed that the LIDT difference between dielectric thin film mirrors and metal mirrors becomes smaller.[4] This makes protected metal mirrors a viable alternative option in some cases. The application environment may also impact LIDT. It is known that in a high vacuum, LIDT (S on 1) is dramatically lower than when measured at atmosphere, as in Figure 7.[6]

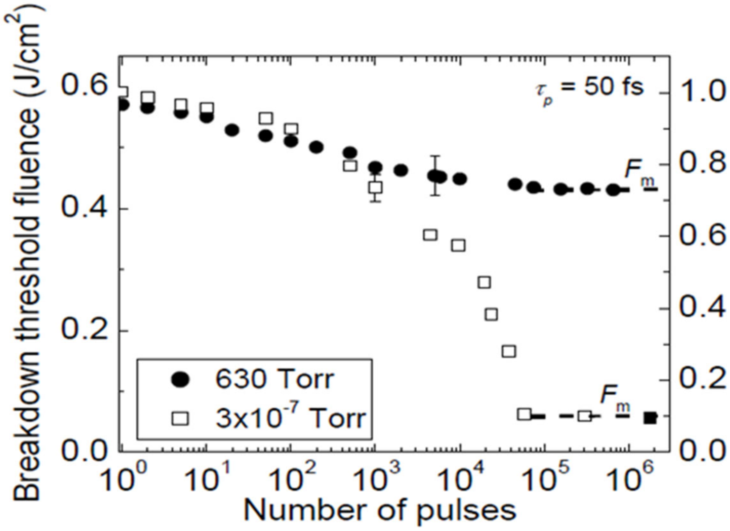

Figure 7. Damage fluence as a function of pulse number (S-on-1) for 50 fs pulses at two different atmospheric pressures.[6]

Optical coating design greatly impacts LIDT for ultrafast laser applications. In general, narrow band mirrors (excluding GTI mirrors) have higher LIDTs than broadband mirrors; S-pol mirrors have higher LIDTs than P-pol at higher angles of incidence; higher reflectivity mirrors have higher LIDTs than lower reflectivity mirrors, and lower GDD mirrors may present higher LIDTs than higher GDD mirrors.

Optimax has developed the design knowledge and process control to ensure its mirrors can reasonably resist ultrafast laser damage. To demonstrate this, a test protocol from the 2021 SPIE laser damage competition[5] was followed to analyze LIDT performance of a mirror manufactured by Optimax of the same specification. The design was a low GDD 515 nm mirror tested at 515 nm, 200 fs, 25° AOI, and S-pol. The results are shown in Figure 8. Compared to the standard QW mirror structure, the Optimax-enhanced LIDT version presents a noticeable improvement and competitive result. Optimax is committed to improving the laser damage threshold for ultrafast laser applications. Current research is focused on understanding failure mechanisms within the multilayer stack and applying materials science-based solutions to improve resistance in the stack at the point of failure, as shown in Figure 9.

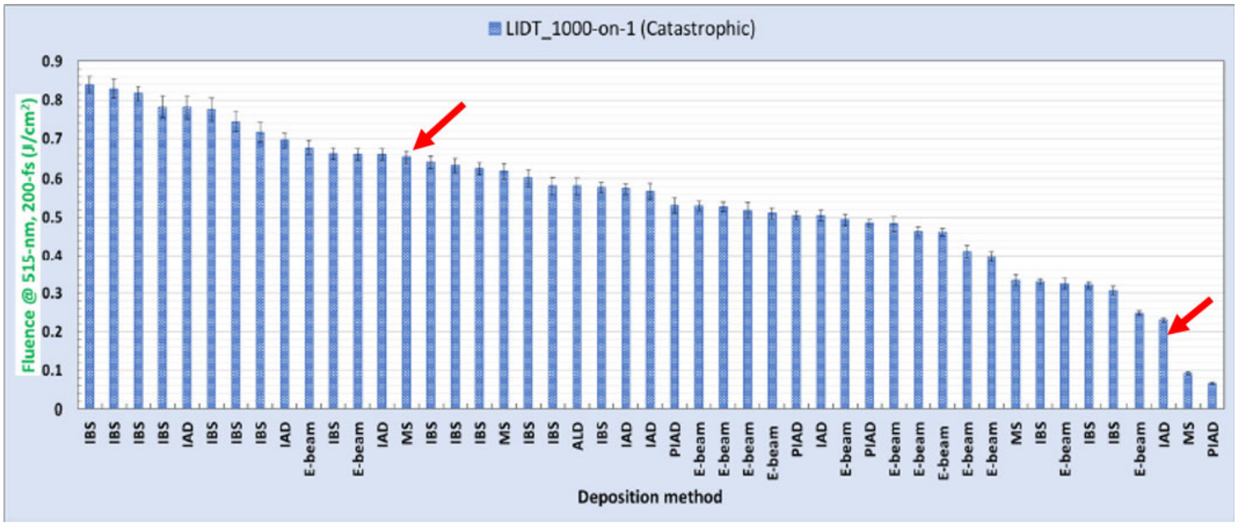

Figure 8. A standard quarter-wave mirror design (right red arrow) and the Optimax enhanced laser damage threshold design (left red arrow) are shown against the 2021 international LIDT competition results.[5]

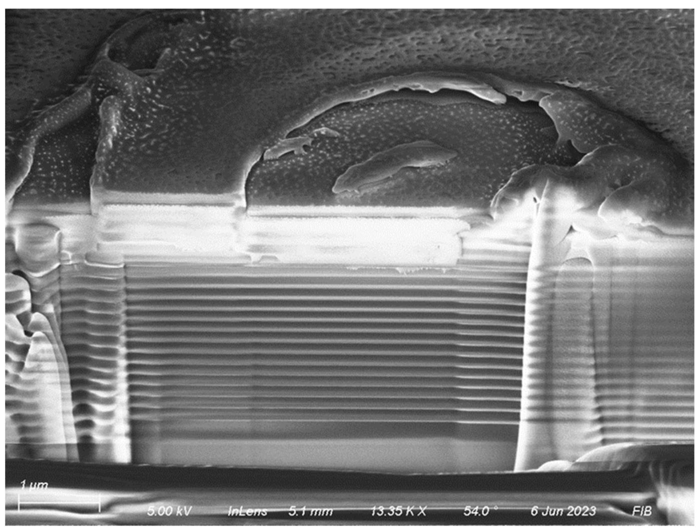

Figure 9. Cross-sectional SEM image of laser damage in an Optimax ultrafast mirror stack, the image shows damage onset occurring at the interface between 2nd layer and 3rd layer in this case.

Conclusion

Optimax has the expertise and equipment to design, manufacture, and measure high-performance ultrafast mirrors. Optimax has a long heritage of rapid prototyping precision optics and now offers the same service for ultrafast mirrors. Optimax's large Ion Beam Sputtering machines can coat optics up to 500 mm in diameter. When programs move to higher volume production, these large machines enable large batch sizes, driving down the cost. Please think of Optimax for your custom and/or challenging ultrafast applications.

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