White Paper

Low temperature apochromatic objectives (LT-APOs)

Performance Aspects and Selection Criteria

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Abstract

We highlight the exceptional characteristics and selection criteria for the **low-temperature apochromatic (LT-APO)** objectives series, including the **long working distance (LWD)** and **ultra-long working distance (ULWD)** options. We categorize the objectives based on their working distance and apochromatic range, showcasing data from various cryogenic experiments to underline their superior performance. This document is designed to assist users with diverse experimental needs in choosing the most suitable LT-APO micro-objective for any given application.

1. General Considerations

Our LT-APO series features micro-objectives with varying focusing power, meticulously engineered for low-temperature operations (down to mK), ultra-high vacuum conditions, and high magnetic fields. It's crucial to recognize that some key performance metrics of micro-objectives can conflict with each other. For instance, while maximizing the numerical aperture (NA) enhances resolution, it also increases sensitivity to focal plane displacement due to the inverse relationship with focal depth (NA^2). Additionally, achieving both high NA and long working distance (WD) with a constant lens diameter is inherently impossible. Balancing high total transmission, large NA, and a wide field of view (FoV) is another complex task, as the latter two typically require more lenses, each contributing to reflectivity and thus reducing overall transmission. Importantly, lens absorption is negligible, and transmission is primarily determined by the anti-reflection (AR) coating. Expanding the spectral bandwidth of the coating usually reduces average transmission within the range. These and other considerations will be detailed in the following sections, focusing on the individual design and performance aspects of our cryogenic apochromatic micro-objectives.

2. Unique interplay of optical and mechanical design elements

The design criteria for NA, FoV, number of lens elements, and the combination of optical glasses for apochromatic color correction are universally applicable to any microscope objective, regardless of environmental conditions. However, conventional microscope objectives from established suppliers are often incompatible with extreme conditions such as ultra-low temperatures, ultra-high vacuum, or high magnetic fields. This incompatibility arises mainly from the traditional use of optical cemented doublets and magnetic materials like aluminum or brass alloys, which are unsuitable for such environments.

Our cryo-compatible micro-objectives overcome these fundamental limitations through innovative paradigm shifts in both optical and mechanical design, supported by novel construction kits and advanced manufacturing technologies.

Key features of our optical design include:

- No cemented lens elements, ensuring durability and performance in extreme conditions.
- Selection of glasses optimized for broad spectral performance with a minimal number of lens elements.
- Use of broadband anti-reflection (AR) coating on all lenses to maximize transmission.

In the mounting technology, we emphasize:

- No use of glue for mounting lenses into mechanical sub-mounts, enhancing stability and reliability.
- Use of titanium with ultra-low concentrations of magnetic impurities for all mechanical elements, ensuring compatibility with high magnetic fields.
- Precise definition of tolerances to compensate for differences in expansion and deformation coefficients of lenses and mount elements upon cooling to the lowest temperatures.

Each assembled objective undergoes rigorous testing with dedicated interferometric measurements before and after a cryogenic cooling cycle to 4.2 K and back to room temperature, ensuring the highest integrity and performance.

3. Apochromatic objective series

Our low-temperature apochromatic objectives are available in three distinct product lines, each designed to meet specific experimental needs:

- **LT-APO** Standard objectives: Featuring a NA of 0.80 – 0.82 and a WD of 0.55 – 0.70 mm.
- **LT-APO/LWD** Long working distance series: Offering an NA of 0.63 – 0.65 and a WD of 5.0 mm.
- **LT-APO/ULWD** Ultra-long working distance line: Ideal for diamond high-pressure cells, with an NA of 0.35 and a WD of 12.0 mm.

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4. Apochromatic range

Our micro-objectives ensure true color representation in absorption, reflection, or emission applications through their apochromatic design.

The standard **LT-APO** series is subdivided into the following spectral bands:
- VIO (405 – 470 nm),
- VIS (465 – 590 nm),
- 532RAMAN (520 – 695 nm),
- VISIR (565 – 770 nm),
- 633RAMAN (632 – 885 nm),
- NIR (700 – 980 nm),
- IR (985 – 1350 nm),
- TELECOM (1170 – 1580 nm).

The **LT-APO/LWD** long working distance line features three versions:
- LWD-VIS (480 – 570 nm),
- LWD-VISIR (570 – 730 nm),
- LWD-NIR (725 – 970 nm).

The **LT-APO/ULWD** ultra-long working distance line for diamond pressure cells comprises two types:
- ULWD-VISIR (520 – 870 nm),
- ULWD-NIR (670 – 1105 nm).

For most applications, the apochromatic range is the primary selection criterion. The specifications and characteristics are determined by the spectral chromatic shift, as detailed in the data sheets for each objective. This is exemplified in Fig. 1, which compares three selected LT-APOs with an aspheric lens featuring an NA of 0.55.

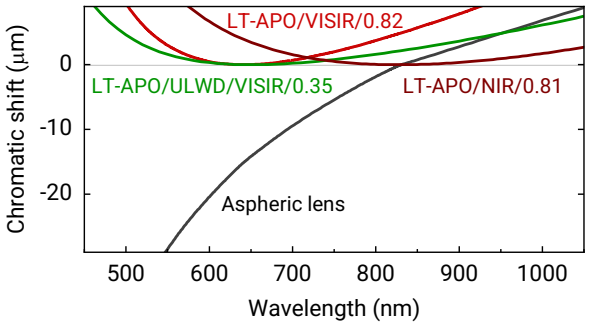

Fig. 1: *Chromatic shift of selected LT-APOs compared to a single aspheric lens with NA = 0.55.*

Fig. 1 illustrates that a single aspheric lens with a chromatic shift of more than 20 µm in the 600 – 1000 nm range compromises broad-band operation. The axial focal plane position will strongly depend on the wavelength. To highlight this important spectroscopic aspect, Fig. 2 compares an LT-APO/NIR/0.81 with an aspheric lens in confocal back-scattering detection of broad-band white light.

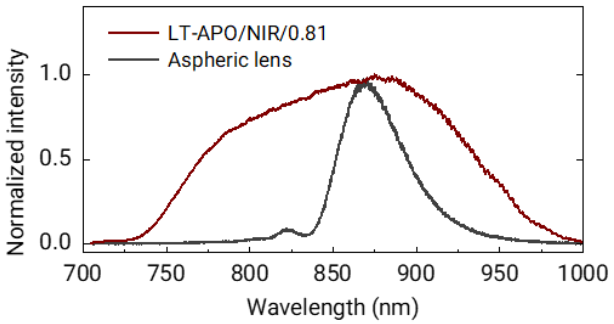

Fig. 2: *Broad-band white light reflection spectrum recorded in confocal back-scattering geometry with an aspheric lens and an LT-APO/NIR/0.81. Note the factor of ~4 smaller full width at half-maximum detection bandwidth of the aspheric lens.*

The spectrum's dependence on chromatic focal shift for the aspheric lens is shown in Fig. 3, which monitors the reflected white light spectrum for three different focal plane positions.

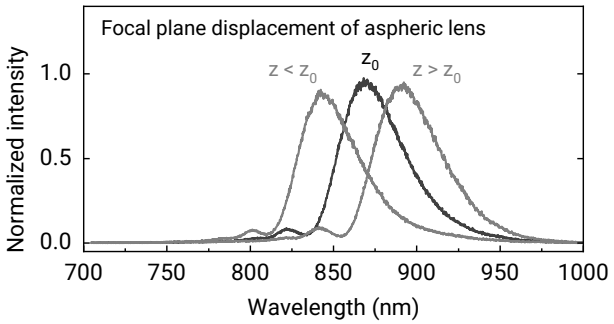

Fig. 3: *Broad-band white light reflection spectrum of an aspheric lens for three axial focal plane positions z (z_0 refers to the focal plane position in Fig. 2).*

Selectivity to a limited color range and sensitivity to focal plane displacement can compromise spectral integrity in confocal spectroscopy. For samples with diverse spectral features, this implies a loss of information, which can be mitigated by using LT-APOs. Fig. 4 demonstrates broad-band detection with an LT-APO/VISIR/0.82, capturing multiple faint vibronic sidebands within a 200 nm spectral window without axial readjustment.

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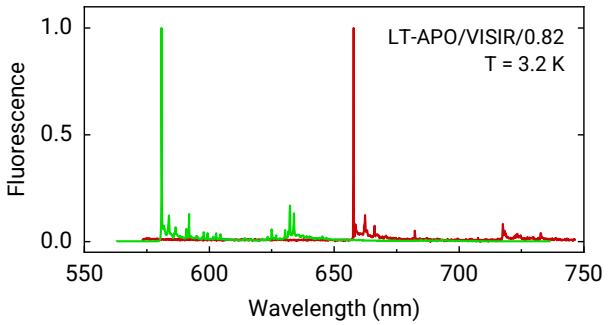

Fig. 4: *Single molecule fluorescence spectra at 3.2 K, with zero-phonon line peaks at 580 nm (green) and 660 nm (red). Note that even the faintest vibronic sidebands within the entire spectral window of 200 nm are captured by the LT-APO/VISIR/0.82 with an APO range of 565 – 770 nm and without the need for axial readjustment of the focal plane.*

The delicate features of both molecule-characteristic vibronic sidebands [1] are simultaneously clearly resolved despite more than 50 nm redshift from the respective zero-phonon lines without the need for realignment. Such spectral features would remain undetected with an aspheric lens with a full-width at half-maximum detection bandwidth below 50 nm in the near-infrared and an even smaller bandwidth in the visible range (see slope in Fig. 1).

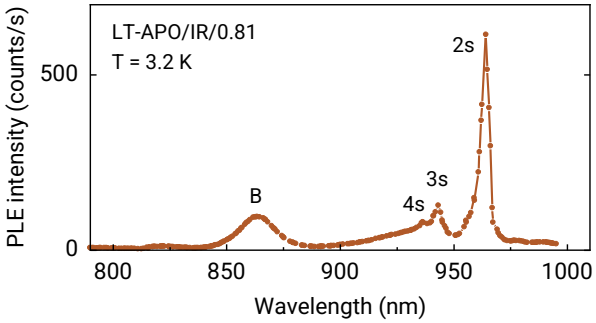

Fig. 5: *Photoluminescence excitation (PLE) spectrum of monolayer $MoTe_2$ in a spectral bandwidth of 200 nm (with labels of characteristic exciton resonances), recorded at 3.2 K with an LT-APO/IR/0.81.*

In addition to fluorescence or photoluminescence, quantitative photoluminescence excitation (PLE) spectroscopy relies on apochromaticity. Fig. 5 shows the PLE spectrum of semiconducting monolayer $MoTe_2$, with peak resonances distributed over a 200 nm spectral window in the near-infrared range [2]. Performing these measurements with an aspheric lens would require a sophisticated alignment procedure to ensure the genuine intensity ratios over the spectral range.

5. Peak intensity

The peak intensity normalized to a perfect lens is a crucial design parameter, quantifying the transmission throughput of an objective relative to an idealized, perfectly transparent imaging lens. Due to the non-ideal flatness of the chromatic shift across the apochromatic range (as shown in Fig. 1), the coupling of chromatic and spherical aberrations results in wavelength-dependent variations in the transmitted peak intensity. This is exemplified in Fig. 6 for the LT-APO/NIR/0.81, which shows simulation results for the transmitted peak intensity at selected wavelengths used to set the focal plane by minimizing the lateral focal spot size.

Understanding the variation in peak intensity with the wavelength used to define the axial focal plane position in best-focus simulations is vital for experimental applications. The effective apochromatic range depends on the actual wavelength chosen to experimentally define the focal plane (e.g., using criteria such as the smallest focal spot size or maximum collection in back-scattering geometry), as shown in Fig. 6. For wavelengths around the minimum of the chromatic focal shift curves (as in Fig. 1), the apochromatic range is narrower compared to wavelengths near the boundaries of the APO range. However, depending on the reference wavelength, limited spectral regions within the APO range may exhibit peak intensity values below 0.8. According to the simulations in Fig. 6, the maximum APO range without nodes in peak intensity below the diffraction limit of 0.8 is anticipated for the LT-APO/NIR/0.81 at wavelengths around 975 nm.

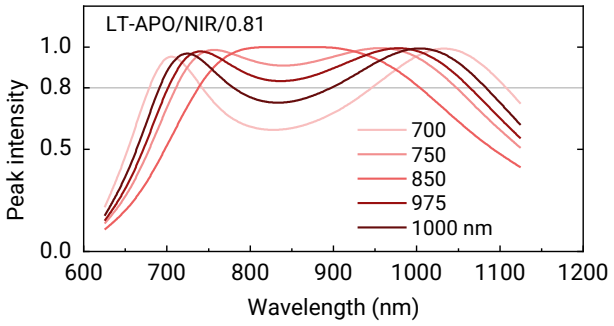

Fig. 6: *Simulations of the peak intensity normalized to a perfect lens for the LT-APO/NIR/0.81, with focal planes defined monochromatically at selected wavelengths between 700 to 1000 nm. The grey horizontal line at 0.8 indicates the lower bound of diffraction-limited performance.*

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6. Transmission

The transmission of any LT-APO objective will not be strictly 1.0 as in simulations but will be slightly reduced due to reflections at every lens-air interface. These reflections can be minimized with antireflection (AR) coatings. The transmission (T) range of LT-APOs is divided according to their respective AR coatings into three spectral bands:

- Visible to near-infrared (400 – 1000 nm)
- Near-infrared to telecom (520/600 – 1600 nm)
- Broadband (400 – 1600 nm)

Within these spectral windows, the overall transmission T through any LT-APO objective is above 0.8, when averaged over the entire spectral range of the coating. The general trade-off for AR coating choice is between the spectral bandwidth and the transmission characteristics. While it is technically possible to reduce the reflectance of the coating over an even more extended spectral range with a more complex AR coating design, this typically comes with increased risk of batch-to-batch variations and higher costs.

7. Field of view

The Field of View (FoV) quantifies the area in the focal plane with diffraction-limited imaging. The FoV depends on the NA and varies across the LT-APO series, as shown in Tab. 1 for three selected objectives.

Objective type	NA	WD (mm)	FoV (Ø in µm)
LT-APO/VISIR	0.82	0.6	70
LT-APO/LWD/VISIR	0.65	5.0	50
LT-APO/ULWD/NIR	0.36	12.0	80

Tab. 1: *Numerical aperture, working distance, and field of view for selected standard, LWD, and ULWD versions of LT-APO objectives.*

It is important to emphasize that our LT-APO objectives are designed for confocal operation and thus have a limited planar FoV compared to Plan-APOs. The diameter of the focal area with diffraction-limited imaging quality ranges between 50 and 80 µm for different LT-APO objectives. This limitation does not imply that image aberrations set in dramatically beyond the FoV but rather emerge as a gradual degradation of image integrity, as shown in Fig. 7.

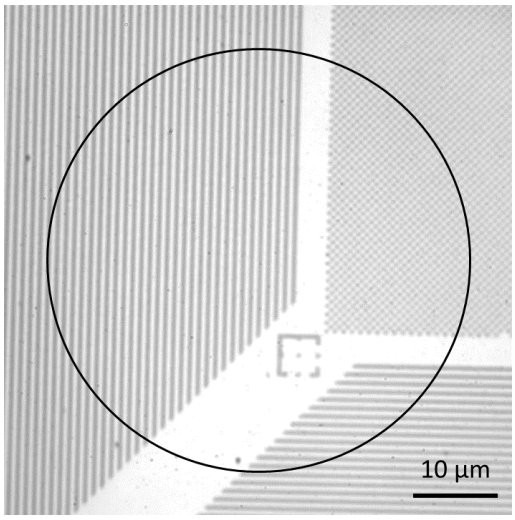

Fig. 7: *Image of a test structure with horizontal and vertical stripes and a checkerboard pattern in the upper right corner. The characteristic length scale of the grey-white modulation in the structure is 500 nm, the circle delimits an image area with a diameter of 50 µm.*

8. Wide-field imaging

The Field of View (FoV) is crucial not only for reflection imaging but also for emission detection applications, including wide-field photoluminescence spectroscopy. Fig. 8 demonstrates that the triangular shape of a $MoSe_2$ monolayer crystal (synthesized by chemical vapor deposition on a Si/SiO_2 substrate, with the respective atomic force micrograph shown in the left panel) is fully preserved in wide-field photoluminescence imaging at 3.2 K (right panel). This example highlights correlations between photoluminescence intensity and defects, such as the small triangular bilayer in the flake center and surface adsorbates at both left and right edges of the monolayer triangle [3].

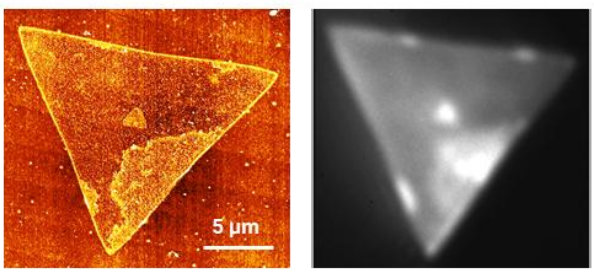

Fig. 8: *Topography of a triangular single-crystal monolayer $MoSe_2$ flake in atomic force microscopy (left panel) and optical wide-field photoluminescence imaging (right panel). The geometrical integrity of the triangle with edge lengths of ~20 µm is preserved in wide-field imaging.*

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9. Polarization integrity in high magnetic fields

The optical elements of LT-APO objectives use glass lenses without birefringence, which is crucial for polarimetric applications requiring polarization integrity in both circular and linear basis in transmission and back-scattering reflection geometries.

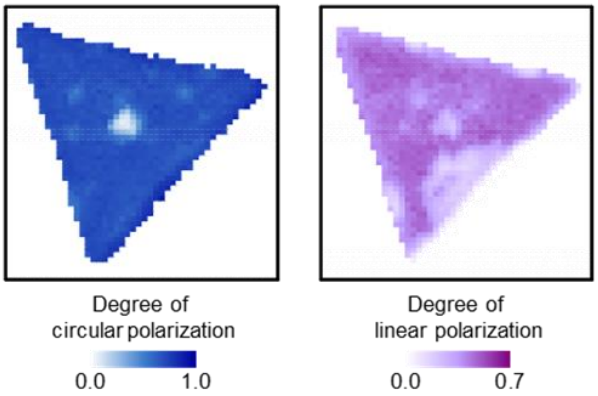

Fig. 9: *Raster-scan polarimetric maps of the same monolayer $MoSe_2$ as in Fig. 8, recorded at 3.2 K. The false-color maps show the degrees of circular (left panel) and linear (right panel) polarization in the photoluminescence of the exciton transition, corresponding to exciton valley polarization and coherence, respectively.*

Fig. 9 and Fig. 10 provide examples of polarimetric applications, visualizing color-coded degrees of circular polarization, linear polarization, and changes in the degree of circular polarization with magnetic field for the $MoSe_2$ flake shown in Fig. 8.

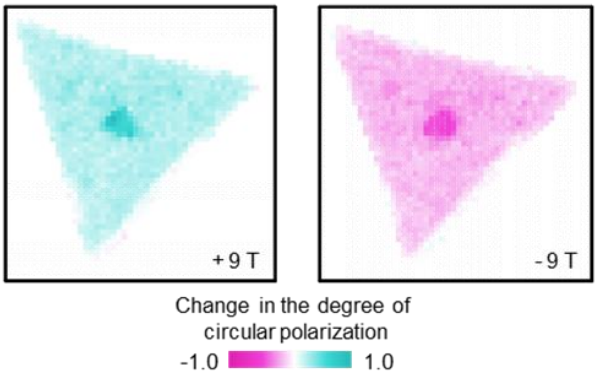

Fig. 10: *Polarimetry of the same $MoSe_2$ flake as in Fig. 8, subjected to high magnetic fields. Note that the color-coded change in the degree of circular polarization at +9 T (left panel) and –9 T (right panel) with respect to 0 T is exclusively due to the valley Zeeman physics of excitons in monolayer MoS_2.*

While circular polarization is insensitive to magnetic fields, linear polarization exhibits in-plane rotation due to the well-known Faraday effect. This rotation must be calibrated at the relevant wavelength and temperature for precise polarimetry.

10. Conclusion

In this whitepaper, we have detailed the design principles, performance characteristics, and selection criteria for the low-temperature apochromatic (LT-APO) series objectives. These objectives are specifically engineered to operate under extreme conditions, such as ultra-low temperatures, ultra-high vacuum, and high magnetic fields, making them an indispensable tool for cutting-edge scientific research. The LT-APO series, with its standard, long working distance (LWD), and ultra-long working distance (ULWD) product lines, offers a range of options tailored to a variety of experimental requirements. The apochromatic design ensures true color representation across various spectral bands, which is critical for applications involving precise chromatic correction.

We have highlighted key performance aspects, including peak intensity, transmission, field of view, wide-field imaging, and polarization integrity. These parameters are crucial for achieving high-quality imaging and spectroscopy results, as demonstrated through detailed simulations and experimental data. Our innovative approach to both optical and mechanical design, supported by advanced manufacturing technologies, addresses the limitations of conventional microscope objectives. This ensures that our LT-APOs deliver exceptional performance and reliability in challenging experimental environments.

We are pioneers of cryogenic apochromatic imaging and the leading provider of LT-APO micro-objectives, which have set the benchmark for quality and performance in the industry. The unique capabilities of our technology enable researchers to achieve results that would be difficult to achieve otherwise.

This whitepaper is intended to serve as a resource for academic researchers, guiding them in selecting the most suitable LT-APO micro-objective for their specific applications. By providing a comprehensive overview of the capabilities and advantages of our LT-APO series, we aim to support the advancement of scientific research and discovery.

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[2] Unpublished data, courtesy of S. Zhao, LMU München.

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