Technical note

Thermo Fisher SCIENTIFIC

Advancing FTIR microscopy with innovative aspherical Schwarzschild objective design

Industry/Application:
Improving FTIR microscopy

Products used:
Thermo Scientific™ Nicolet™ RaptIR™+ FTIR Microscope

Goals:
Summarize the innovative design and improved performance of the objective used in the RaptIR family of FTIR microscopes.

Key Words:
Modified Schwarzschild design, aspherical mirrors, off-axis geometry, modulation transfer function, interferometry, spot diagram, diffraction limited resolution

Key Benefits:
The RaptIR family of FTIR microscopes employs carefully designed aspherical mirrors and an off-axis geometry for improved image quality and spatial resolution approaching the diffraction limit.

Introduction

Infrared (IR) microscopy enables chemical characterization at the micrometer scale but is fundamentally limited by diffraction due to the long wavelengths of IR radiation. Achieving high spatial resolution while maintaining optical throughput remains a central challenge in FTIR microscope design. The pursuit of diffraction-limited spatial resolution requires reducing diffraction from optical components such as objectives and apertures. This technical note will focus on an objective design that provides improved performance.

Refractive glass objectives like those typically associated with visible microscopy are not appropriate for use with infrared microscopy because they are not transparent to a majority of mid-infrared radiation. While it is possible to utilize lenses made from materials that are transparent in portions of the mid-IR region, a more practical methodology is to employ reflective optics. Reflective optics do not display the chromatic aberrations common to refractive elements, and they can accommodate a broad spectral range.

Reflective optics are used quite extensively in telescope applications and are also used in microscope objectives. The Schwarzschild design (also known as reverse Cassegrain) is an arrangement of reflective optics often used for microscope objectives. The basic layout is shown in Figure 1. The objective uses a convex secondary mirror to reflect light onto a concave primary mirror that focuses the light. The primary mirror has an opening in it that allows light to pass through to the secondary mirror, and the secondary mirror is suspended in the light path. A disadvantage of this type of objective is that the secondary mirror blocks part of the light and this obscuration diminishes the brightness, reduces the image quality, and lowers the contrast. Contrast is integral to spatial resolution, so obscuration also moderates spatial resolution. The classical design of these objectives used spherical mirrors. The issue with the use of spherical mirrors is that the reflection angles are fixed and this in turn limits flexibility in objective design. This imposes limitations on important aspects of objectives such as the field of view, working distance, numerical aperture, and obscuration. The use of aspherical mirrors provides more freedom in terms of the design of modified Schwarzschild type objectives, allowing for improvements in the working distance, field of view, image quality, and spatial resolution. The design and manufacturing of aspherical mirrors can be more complicated, but they provide distinct advantages in freedom of design. Some optical designs can also be much more complex and involve multiple mirrors and reflections in a variety of different configurations, but those more complicated designs will not be discussed here as this discussion will focus on a modified Schwarzschild design with aspherical mirrors.

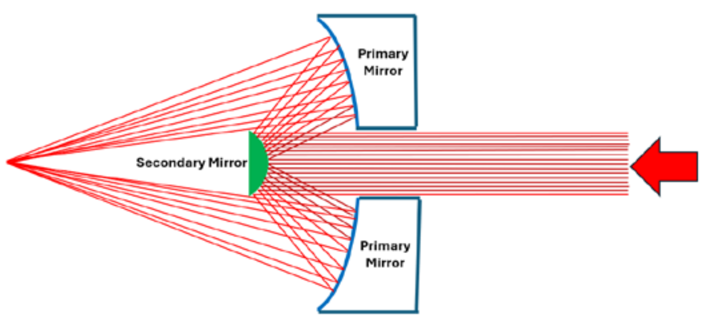

Figure 1. Diagram of a Schwarzschild type reflection objective.

The Nicolet RaptIR+ FTIR microscope is a high-performance instrument that integrates microscopy with FTIR spectroscopy. It is part of the Thermo Scientific™ RaptIR™ family of FTIR microscopes that all utilize patented objectives and condensers based on a modified Schwarzschild layout using specially engineered aspherical mirrors to improve performance and optimize spatial resolution. This note reviews the main points in the patent and the characterization of the resulting objective.[1] The RaptIR family of FTIR microscopes also utilize an off-axis geometry to further improve performance. Data will also be presented related to spatial resolution when collecting infrared spectral data using a RaptIR+ FTIR microscope.

Patent details and demonstrated performance

The innovation described in the patent involves the use of diamond-turned aspherical mirrors for the primary and secondary mirrors in infinity-corrected optics that are based on a non-zero sixth order aspheric parameter. By adjusting the series of aspheric parameters for the mirrors, it is possible to increase the working distance (>20 mm) while maintaining a high numerical aperture (up to 0.65).

The patent includes optical evaluation of an objective with these new innovations to demonstrate improved performance. These tests use visible light and are similar to those that are commonly used for evaluating microscope objectives. The first of these tests is a measure of achievable spatial resolution. This characteristic is determined using a plot of the modulation in contrast measured across equally spaced light and dark lines versus the spacing of those lines. A standard such as the 1951 USAF optical target is typically used for such evaluations.[2] An image of part of a USAF 1951 optical target is shown in Figure 2. The different groups and elements of the USAF target consist of lines and spaces of the same dimensions within a group and varying sizes between groups. The modulation is related to the changes in contrast observed between these lines. If the spacing is large, then positions of complete darkness and complete light (100% contrast) will be observed. As the lines get smaller, the lines become less defined (<100% contrast) and there is a blurring of the image. This can be seen in Figure 2 comparing group 6 lines to group 8 or 9 lines. In the modulation transfer function plot the x axis (line spacing) is expressed as spatial frequency in black/white line pairs per mm (lp/mm). The modulation (contrast) decreases with an increase in spatial frequency (a larger number of line pairs per mm equates to smaller spacing) and reaches a cutoff frequency that is a measure of the spatial resolution achievable with the objective. The modulation transfer function plot from the patent is shown in Figure 3. The plot was generated using light with a wavelength of 587.6 nm and the cutoff is reported at about 650 lp/mm (650 lp/mm is 1.54×10^{-3} mm/lp or 0.77 micron per line). This supports the claim made in the patent filing that the design is capable of achieving a spatial resolution in the visible region of 1 micron or better.

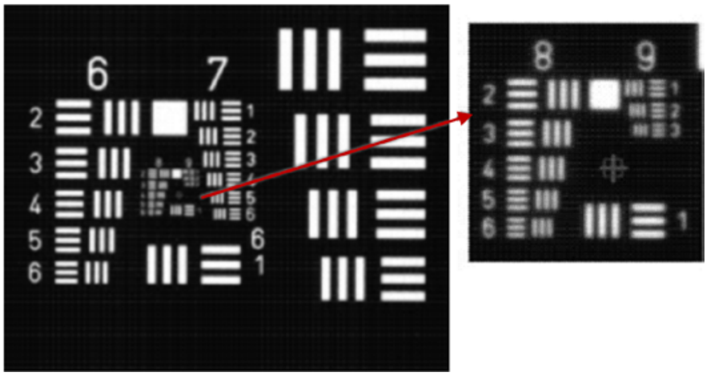

Figure 2. A portion of a USAF 1951 target showing elements of group 6-9. From Y. Min and F.J. Deck, Hybrid Reflective Microscope Objective, 2023 (US 20230168122A1)

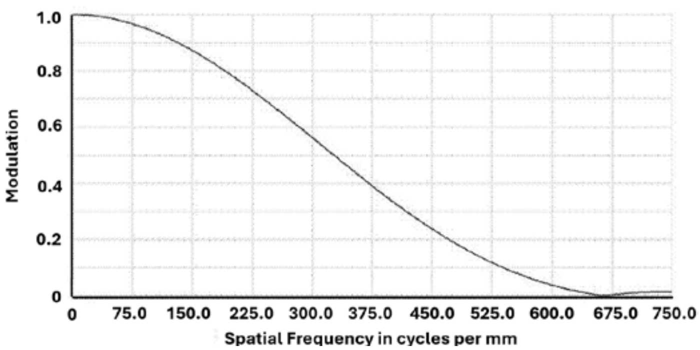

Figure 3. Modulation transfer function plot for 0.5876 microns. From Y. Min and F.J. Deck, Hybrid Reflective Microscope Objective, 2023 (US 20230168122A1)

Interferometers can be used to evaluate optical components, and the interference patterns can be used to observe defects and aberrations. Different types of interferometers have been used to gather various types of information about optical components.[3] A full discussion of these is beyond the scope of this note but an example will be presented in terms of further characterizing this aspherical Schwarzschild design objective. The interference pattern generated from this objective shown in Figure 4 shows a series of regularly spaced straight-line fringes with no distortions across the exit pupil. There is no evidence of curvature or distortions that would indicate aberrations or defects. This demonstrates that this objective is expected to produce high-quality, aberration-free images.

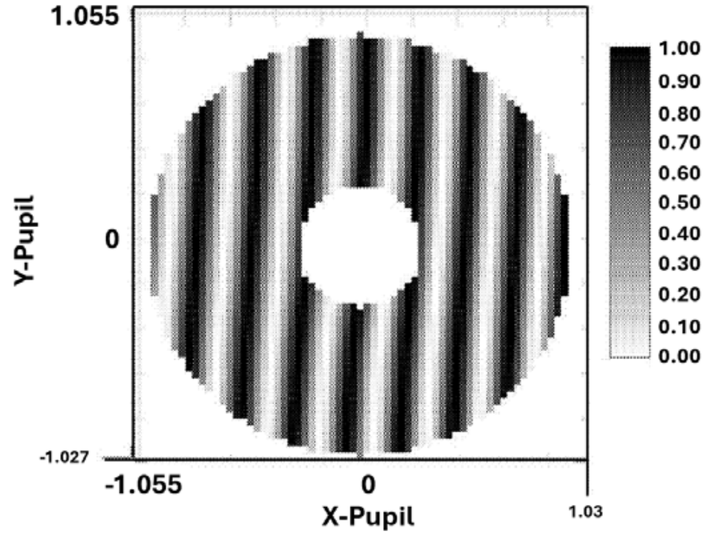

Figure 4. Interferogram Plot: 0.5876 microns at 0.0000, 0.1250; Peak to valley = 0.4079 waves; Fringes/wave = 1.0000; Exit pupil diameter = 1.7537 mm. From Y. Min and F.J. Deck, Hybrid Reflective Microscope Objective, 2023 (US 20230168122A1)

Spot diagrams are commonly used for evaluating the performance of optical systems.[4] They are a graphical way to check the quality of optical systems, and distortions in the spot diagram images are directly correlated to different types of aberrations (astigmatism, coma, spherical aberration, chromatic aberration). Spot diagrams are generated based on ray traces from single points in the object plane to positions on the image plane. Coordinates where the ray traces impinge on the image plane are plotted and these form the spot diagram. The distribution of the points indicates the spot size; distortions in the shapes indicate different types of aberrations. The spot size can be compared to the airy radius to judge how it compares to the diffraction limit. Figure 5 shows spot diagrams generated using the new objective design. The different IMA (image mean angle) fields represent different angles or distances between the optical axis of the mirror and the image produced. The black circles in the spot diagrams represent the Airy radius (an effective proxy for the diffraction limit). The distortions in shape are not large, so any aberration effects are small, and the RMS radii are all smaller than the Airy radius, indicating diffraction-limited image quality.

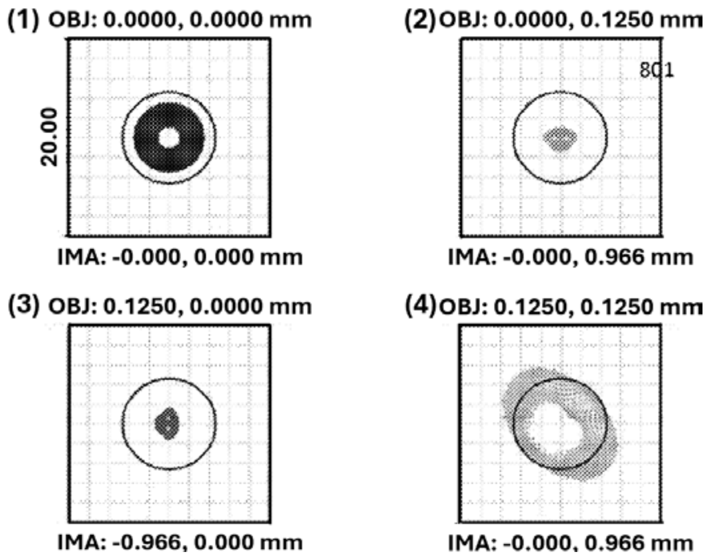

Figure 5. Spot diagrams: Black circles indicate Airy radius 4.626 microns; Field 1 RMS radius = 2.630 μm; Field 2 RMS radius = 0.932 μm; Field 3 RMS radius = 0.932 μm; Field 4 RMS radius = 4.340 μm; Box width = 20. From Y. Min and F.J. Deck, *Hybrid Reflective Microscope Objective*, 2023 (US 20230168122A1)

The tests of the new objective design included in the patent are typical of those used to characterize visible light objectives. These tests indicate diffraction-limited image quality and achievable spatial resolution below 1 micron (0.77 microns at 587.6 nm) are achievable with this new objective design. The improvement in visual images is important because visual images are used to locate important areas of interest, and the correlation between the visible images and infrared analysis is a major advantage of FTIR microscopy.

Off-axis geometry

While not discussed in the patent, an off-axis geometry is an additional aspect of the RaptIR FTIR microscope design implemented to improve performance. An off-axis arrangement is used where the optical path is offset in order to circumvent the interference from the secondary mirror and mounts. This reduces obscuration and improves illumination, leading to enhanced performance. Using symmetric spherical mirrors can cause issues with an off-axis geometry and introduce additional detrimental aberrations. However, the use of aspherical mirrors gives additional freedom in design that can accommodate the additional demands of an asymmetrical beam path. This allows for improved throughput while maintaining diffraction-limited image quality.

Experimental: Infrared measurements

While the results of the visible testing are important and could be extrapolated to the longer wavelengths used in FTIR microscopy, it is informative to look at infrared data from a RaptIR+ FTIR microscope outfitted with this new objective to determine the achievable spatial resolution. This section includes infrared data that is not part of the patent but was collected to evaluate infrared performance of the FTIR microscope.

Line maps were collected across the elements (1-6) in group 6 on a USAF 1951 optical target using a RaptIR+ FTIR microscope with a 5 x 5 μm aperture and 1 μm steps in reflection mode. Data were also collected on a cross-section of a 10 μm diameter polystyrene bead mounted in epoxy and sectioned using a microtome. The cross-section was mounted over a hole in a slide to allow for transmission analysis. An area map was collected using a 5 x 5 μm aperture and 1 μm steps.

Results

The data from the line maps acquired from the USAF 1951 optical target were analyzed by plotting the percent reflection at 4000 cm^{-1} as a function of the steps along the line map. The results are shown in Figure 6. The results show a steady decrease in contrast as the thickness of the lines is reduced and the spacing between them gets smaller (increasing line pairs per mm). This data can be used to generate a modulation transfer function plot similar to the one shown previously at 587.6 nm, but in this case at an infrared wavelength (2.5 microns). This is shown in Figure 7. The largest spatial frequency investigated did not reach an absolute cutoff; there was still visible contrast in the data at 114 lp/mm (group 6, element 6). However, this does indicate that a spatial resolution of better than 4.4 microns is achievable at 4000 cm^{-1}.

As part of the discussion of spatial resolution. there is one more concept that should be mentioned: There is a difference between spatial resolution and spectral isolation.

Spatial resolution is based on contrast and the ability to resolve features. But, if the materials being resolved have infrared spectra associated with them and the contrast is below 100%, the result will be a spectrum that represents a mixture of various spectral features from the components—the lower the contrast is, the more of a mixture is present in the spectrum.

The spectral isolation limit is a more complex determination because it is also based on the spectral characteristics of the various components. An example of this can be seen in Figure 8 where the sample is a cross-section of a 10 μm diameter polystyrene sphere embedded in mounting epoxy. The box in Figure 8(a) shows the area on the sample that was mapped. It should be noted that because of the relatively similar sizes of the bead (10 µm diameter) and the aperture (5 x 5 µm) there are limits on the spectral isolation. The polystyrene peak between 3013 and 3034 cm^{-1} was used to generate an infrared image representing the distribution of the polystyrene (see Figure 8(b)). The relative peak area plotted as a function of map steps across the polystyrene bead gave a full width at half maximum of 10 µm, which is the expected diameter of the bead cross-section and was confirmed from the visual image as well as high-resolution Raman microscopic imaging. While it was possible to determine the size of the sample this way it is also important to note that there are still small contributions from the polystyrene peaks in the epoxy spectra beyond the 10 µm diameter. This illustrates that while spatial resolution and spectral isolation are related it is also important to understand the differences.

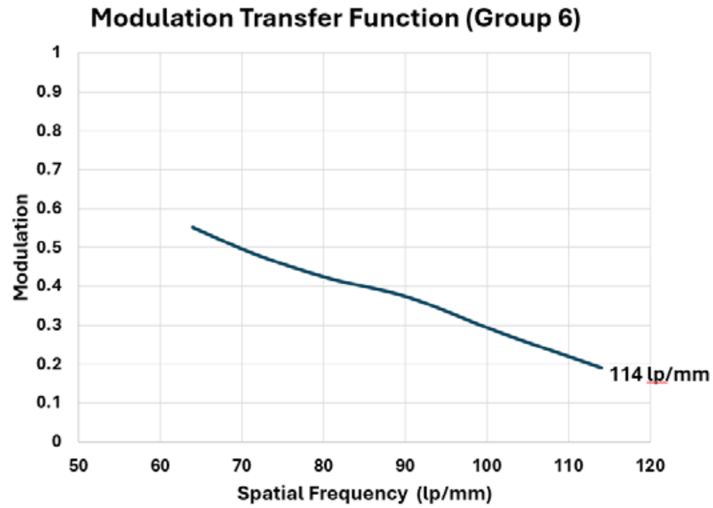

Figure 7. Modulation transfer function plot for infrared spectra at 4000 cm^{-1} (2.5 µm) for data collected across group 6 elements 1-6. The smallest value is from 6.6 at 114 lp/mm or a line width of 4.4 µm. This represents a spatial resolution of 4.4 µm or better.

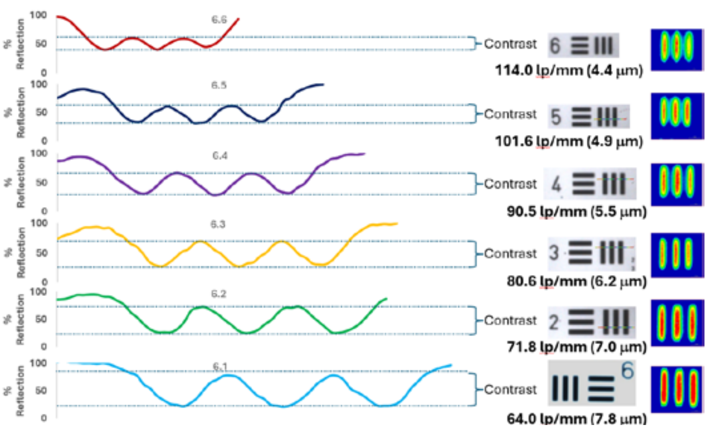

Figure 6. Contrast across group 6 elements 1-6 based on percent reflection at 4000 cm^{-1}.

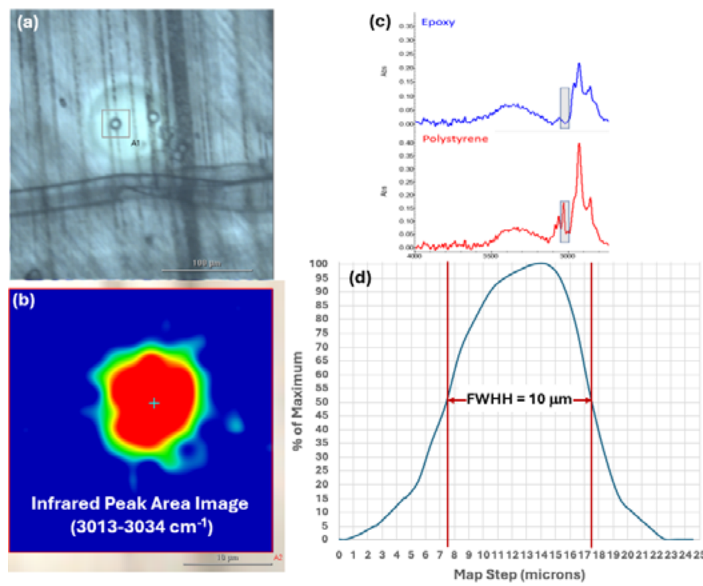

Figure 8. (a) Visual image of a cross-section of a 10 µm polystyrene bead embedded in mounting epoxy. The box represents the area that was analyzed. (b) An infrared image based on the area of a polystyrene peak between 3013-3034 cm^{-1} where red indicates higher polystyrene content and blue lower or no polystyrene content. (c) Spectra showing the region used to generate the infrared image and data in (d). (d) Plot of relative peak area versus map steps across the polystyrene bead with a full width at half height of 10 µm.

Conclusions

The data presented in the patent for this new design of a modified Schwarzschild type objective using specially engineered aspherical mirrors indicate that the objective minimizes diffraction effects and is operating essentially at the diffraction limit. This was supported by the modulation transfer function plot and the spot diagrams. The interferogram data showed a high-quality image with no obvious distortions due to aberrations.

The use of an off-axis geometry in the RaptIR+ FTIR microscope is supported by using aspherical mirrors. This reduces the effects of obscuration and increases throughput, further improving illumination and performance.

A modulation transfer function plot for infrared data collected using a RaptIR+ FTIR microscope equipped with the new objective indicated that a spatial resolution better than 4.4 µm is expected at 4000 cm^{-1}. This value of 4000 cm^{-1} represents a typical upper limit for the mid-IR region, and it should be noted that the spatial resolution will decrease across the infrared spectrum as the wavenumbers become smaller and wavelengths longer. This variation with wavelength is a fundamental property of the diffraction limit of light.

Advances in objective design can help push the limits to get the highest spatial resolution possible and provide high quality images. This is important for both the quality of the visible images of the samples being analyzed and the associated infrared spectra, including infrared images based on those spectra. The new design of the objective for the RaptIR family of FTIR microscopes helps achieve significantly improved results compared to earlier designs.

References

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