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IR spectrometer using 90-degree off-axis parabolic mirrors

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ABSTRACT

A gated spectrometer has been designed for real-time, pulsed infrared (IR) studies at the National Synchrotron Light Source at the Brookhaven National Laboratory. A pair of 90-degree, off-axis parabolic mirrors are used to relay the light from an entrance slit to an output IR recording camera. With an initial wavelength range of 1500–4500 nm required, gratings could not be used in the spectrometer because grating orders would overlap. A magnesium oxide prism, placed between these parabolic mirrors, serves as the dispersion element. The spectrometer is doubly telecentric. With proper choice of the air spacing between the prism and the second parabolic mirror, any spectral region of interest within the InSb camera array's sensitivity region can be recorded. The wavelengths leaving the second parabolic mirror are collimated, thereby relaxing the camera positioning tolerance. To set up the instrument, two different wavelength (visible) lasers are introduced at the entrance slit and made collinear with the optical axis via flip mirrors. After dispersion by the prism, these two laser beams are directed to tick marks located on the outside housing of the gated IR camera. This provides first-order wavelength calibration for the instrument. Light that is reflected off the front prism face is coupled into a high-speed detector to verify steady radiance during the gated spectral imaging. Alignment features include tick marks on the prism and parabolic mirrors. This instrument was designed to complement single-point pyrometry, which provides continuous time histories of a small collection of spots from shock-heated targets.

Keywords: mid-IR imaging, IR spectrometer, off-axis parabolic mirrors, InSb IR camera, Brookhaven National Synchrotron Light Source

1. INTRODUCTION

A spectrometer is used to analyze a beam of light into its component colors. Real time infrared spectroscopy requires simultaneous separation and acquisition of light across a broad wavelength range.[1] For example, the vacuum ultraviolet (VUV) ring at the National Synchrotron Light Source (NSLS) emits one or more broad wavelength (including the IR) pulses every 170 ns. Standard spectrometers, based on a rotating diffraction grating, cannot utilize this light in a real-time fashion, rather, they require a lengthy time to scan the light intensities at each wavelength.

For a wide IR wavelength range of 1500–4500 nm, reflective optical elements are required. Using flat mirrors to relay the light through the prism would send a spectral distribution towards the recording camera with an angular dependence. As the air spacing between the dispersing element and the camera changes, different wavelength ranges would be recorded. Thus, precise calibration would be hard to maintain. An additional complication is that the synchrotron light has a different amount of divergence along the up/down axis compared to the left/right axis.

Diamond-turned, 90-degree, off-axis parabolic mirrors have been used as a 1:1 relay system.[2] Off-axis parabolic mirrors combine the functionality of relay lenses and turning mirrors. If light is nearly collimated at the start, the light will also be nearly collimated after leaving the pair of parabolic mirrors. If the pair of parabolic mirrors is not orientated tip to tip, then image rotation up to 60 degrees can occur. This can be detrimental for imaging applications.

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2. OPTICAL DESIGN

A new spectrometer configuration designed for real-time synchrotron studies in shown in Figure 1. Light from the synchrotron is directed onto a 0.2 mm wide × 9 mm long entrance slit. The 0.2-mm width controls wavelength resolution, while the 9-mm length allows spatial sampling of the input beam. A 90-degree off-axis parabolic mirror collimates light from the slit. The collimated light is sent into a dispersing prism, the output of which is recollimated by a second parabolic mirror and recorded with an IR imaging camera. Wavelength resolution of this spectrometer is limited primarily by the divergence of the IR synchrotron light source.

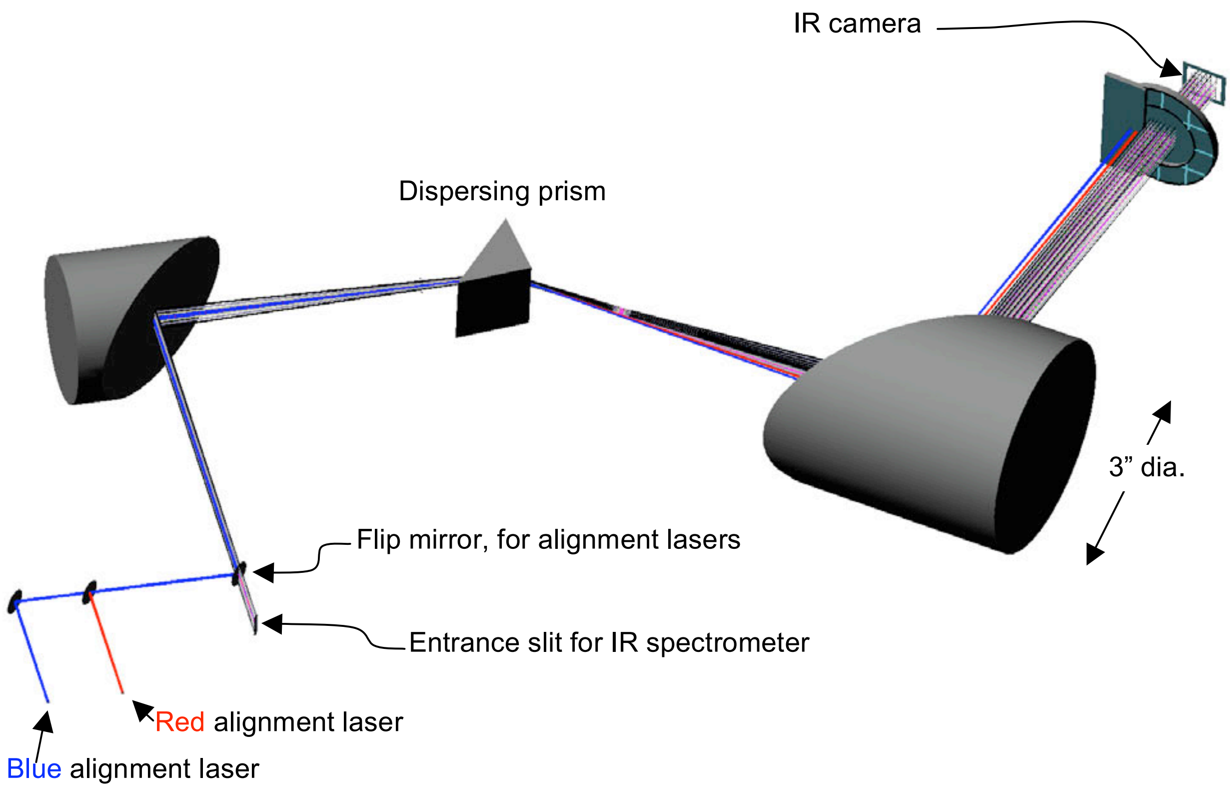

Fig. 1. Light from the Brookhaven NSLS entering into an entrance slit. The slit measures 0.2 mm wide by 9 mm long. This will allow spatial sampling of the light along 9 mm of the synchrotron light beam.

The pair of parabolic mirrors provide focusing power and turning control of the input light. The mirrors are gold coated for optimal reflectance throughout the infrared spectrum. Unlike a lens-based system, the mirrors avoid chromatic aberrations at all wavelengths. Note that the second parabolic mirror is inverted with respect to the first mirror to collimate light dispersed by the prism. This orientation is opposite of an imaging configuration, where the mirror tips would be pointed at one another to minimize aberrations.

A dispersing prism is used in this spectrometer for several reasons. The index of refraction of the prism varies as a function of wavelength, and the different wavelengths exiting the prism will have different angles. With an initial wavelength range of 1500–4500 nm required, gratings could not be used as the dispersing element because grating orders would overlap. Unlike a diffraction grating, light dispersed by a prism is oriented in a single direction instead of multiple orders. This behavior eliminates the need for additional filters and allows broad spectral coverage. The prism does not rotate during the integration time of the IR camera. The prism is constructed from magnesium oxide (MgO), which is transparent in the spectral range of interest (1500–4500 nm) with sufficient dispersion and without birefringence. This material is far more robust than standard infrared materials, such as sodium chloride. The readily available sapphire prism cannot be used within this wavelength range because its birefringence would produce a double image. Both a right-angle and an equilateral prism were examined for this spectrometer. The right-angle prisms proved a better match with off-the-shelf parabolic mirrors.

A fast-gated InSb two-dimensional detector array camera records the complete spectrum. Light entering the camera is collimated, so the camera is not at an imaging plane (as the case with most IR spectrometers). Spectral intensity data are recorded simultaneously, rather than being incrementally scanned over a wavelength range. The IR camera records two-dimensional (2-D) data. A line profile along one dimension and a wavelength spectrum along the other dimension are mapped onto the IR detector array.

Figure 2 is a top view of ray traces passing through all the optical components. By varying the distance from the prism to the second parabolic mirror, different wavelength ranges can be presented to the IR camera. Because the light is collimated between the second parabolic mirror and the camera, the exact distance between these two components is not important. With other types of IR spectrometers this distance has tight tolerancing that affects the spectral calibration.

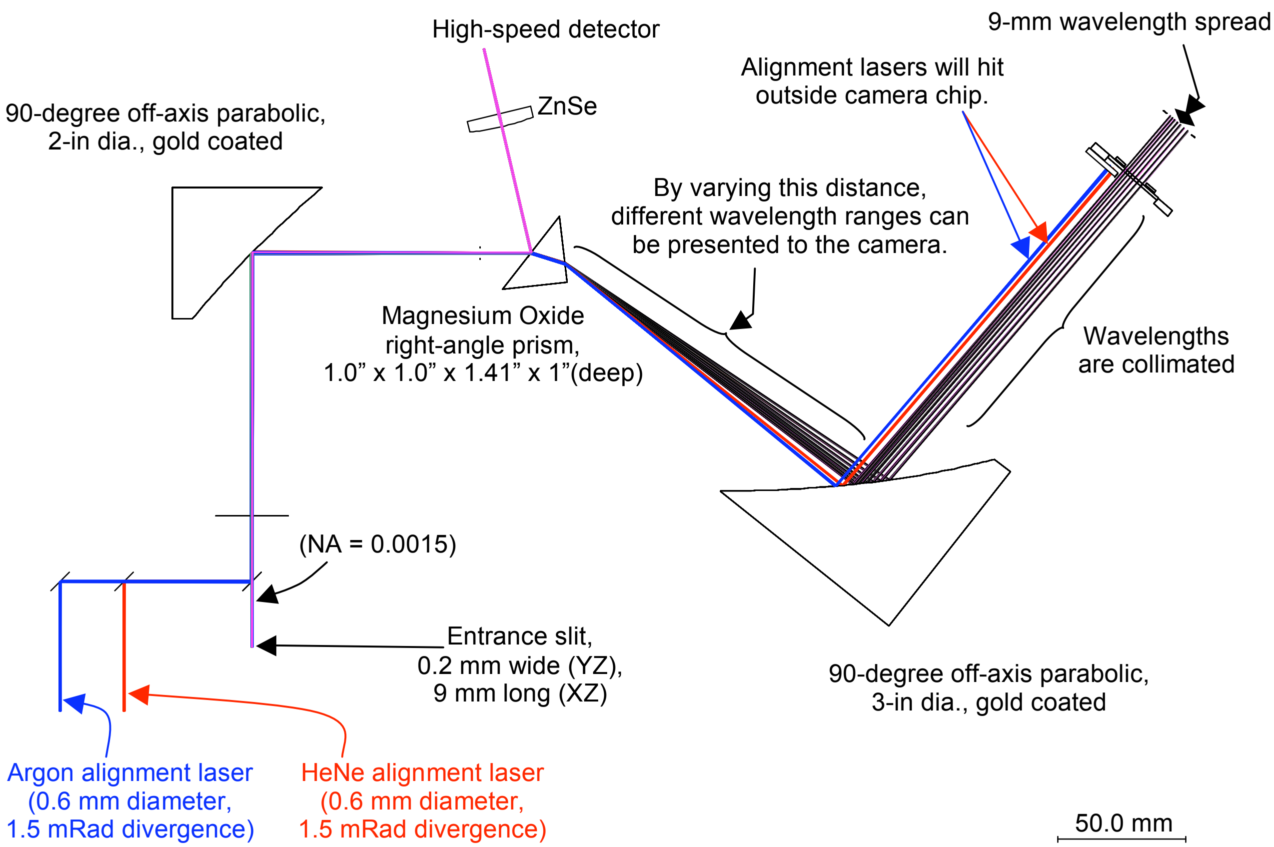

Fig. 2. Optical components used for the IR spectrometer.

Figure 2 also shows how light that is reflected by the front prism facet could be incorporated into a multichannel pyrometer system (only a single channel is shown in this figure). Another 90-degree, off-axis parabolic mirror and beam splitters would be added between the prism and the ZnSe lens. The beam splitters would direct the light into detectors set to record different wavelength bands. Therefore, the continuous spectrum could be obtained in conjunction with time-resolved radiometry to verify that constant radiance exists when the IR camera is gated. A 50/50 IR coating can be applied to the one facet of the prism to reflect the synchrotron light into the pyrometry diagnostic. This instrument was designed to complement single-point pyrometry, which provides continuous time histories of a small collection of spots from shock-heated targets.

Figure 3 is a close-up view of how the light spreads out along the wavelength dimension of the IR detector array. In this view it appears that all wavelengths pass through the cold stop. However, the cold stop is circular and will clip rays that are at the edge of the IR detector array. The wavelengths do not spread equally, but this can be calibrated.

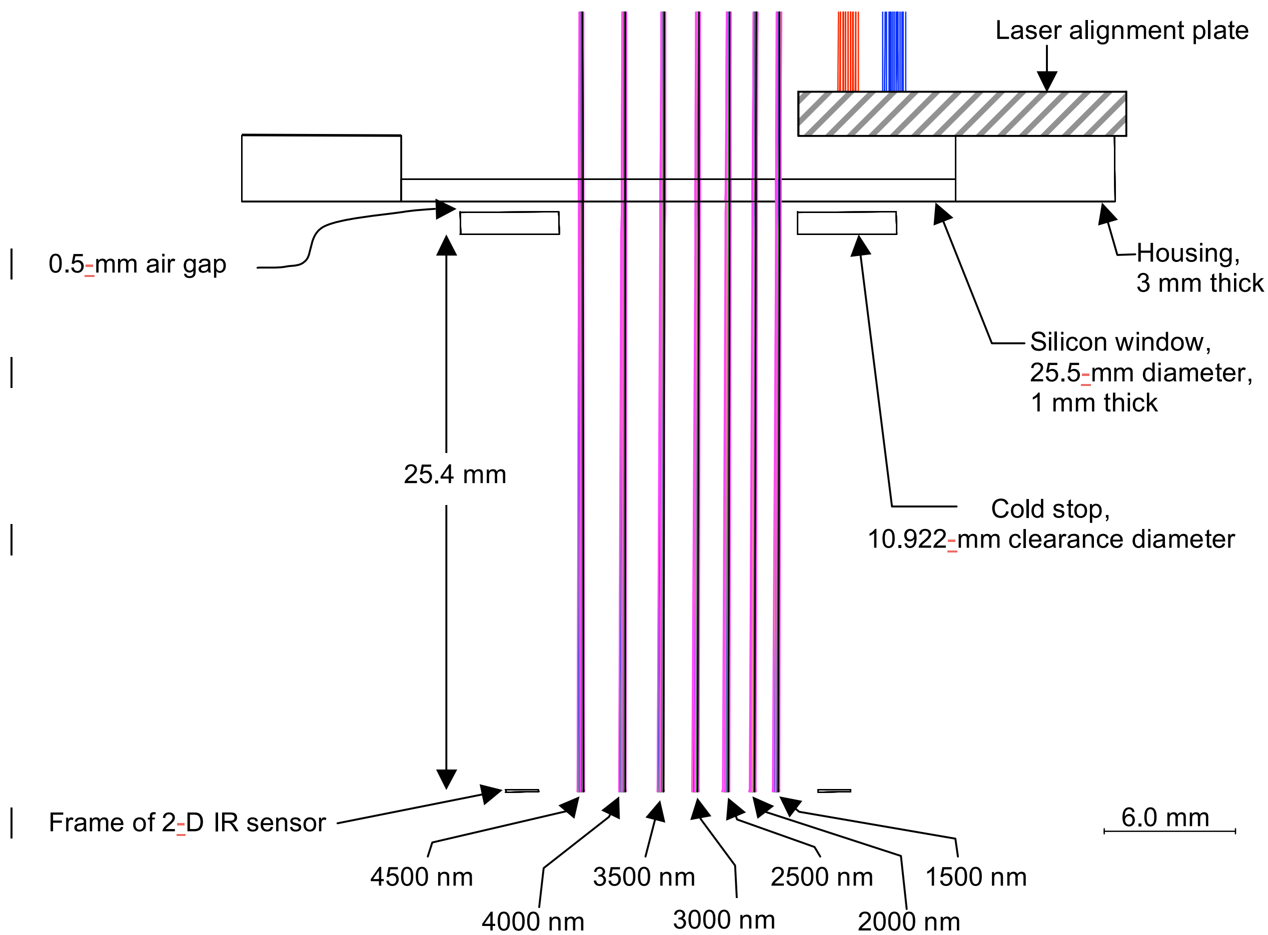

Fig. 3. The light is collimated coming into the IR sensor. The different wavelengths are spread unequally across the IR imaging array. The two alignment lasers are blocked from hitting the silicon window of the IR camera.

3. OPTICAL ALIGNMENT

To set up the instrument, two different visible wavelength lasers are introduced at the entrance slit and made collinear with the optical axis via flip mirrors. After dispersion by the prism, these two laser beams are directed to tick marks located on a plate that is mounted to the outside housing of the gated IR camera. This provides a first-order wavelength calibration. The two alignment laser beams must be <0.6 mm in diameter to ensure precision alignment. Other alignment features include tick marks on the prism and parabolic mirrors.

Figure 4 shows the wavelengths passing through the dispersion prism. Although we attempted to center the light through the prism, centering does not have to be accurate. However, the relative angles for each wavelength are important, and this is independent of how much thickness of MgO they pass through.

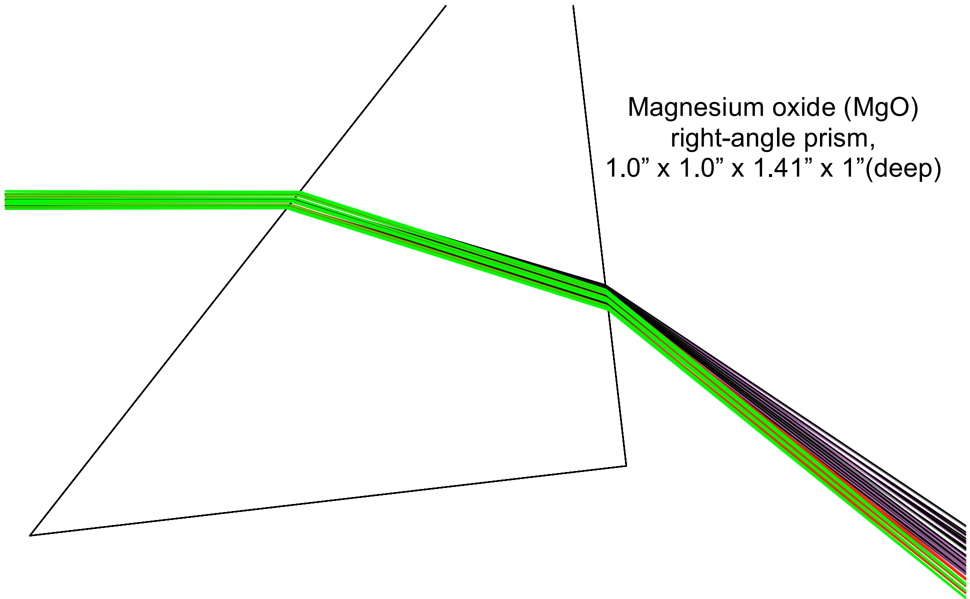

Fig. 4. Ray tracing through the MgO dispersion prism.

Figure 5 shows that light reflects off the second parabolic mirror on its way to the camera. We placed the two alignment lasers off center, so as to place the 1300-nm wavelength at the center of the parabolic mirror. Note that each wavelength will see a different radius of curvature on the mirror.

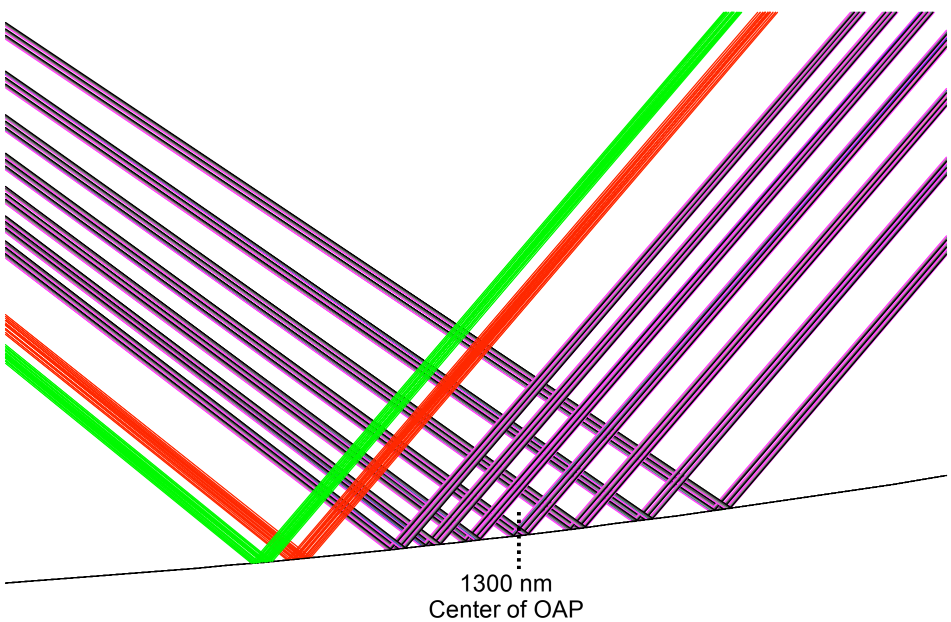

Fig. 5. Ray tracing at the second off-axis parabolic (OAP) mirror.

Figure 6 shows a close-up perspective view of the front of the IR camera. The two visible alignment lasers are aimed at tick marks located on an alignment plate attached to the camera housing. A silicon window protects the camera from visible light. The two alignment laser beams are blocked from reaching the silicon window of the IR camera.

The inside of the IR camera contains a cold stop. Most IR imaging applications require this cold stop when lenses are mounted onto the camera. Our spectrometer does not make use of this cold stop because the light at this location is collimated. As this cold stop cannot be easily removed, it becomes a limiting aperture and will clip light at the edges of the wavelength range. For this application, a rectangular cold stop would work better. Figure 7 is a perspective view showing how this cold stop does not allow as much light collection at the edges of the wavelength range.

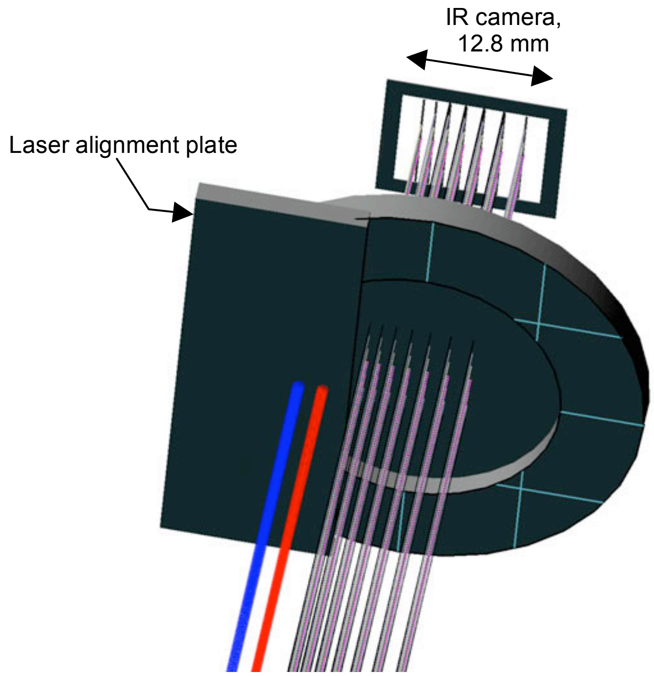

Fig. 6. Close-up perspective view of the IR camera location. The two visible alignment lasers are aimed at tick marks located on an alignment plate attached to the camera housing. A silicon window protects the camera from visible light. Different wavelengths hit different regions of the IR camera array.

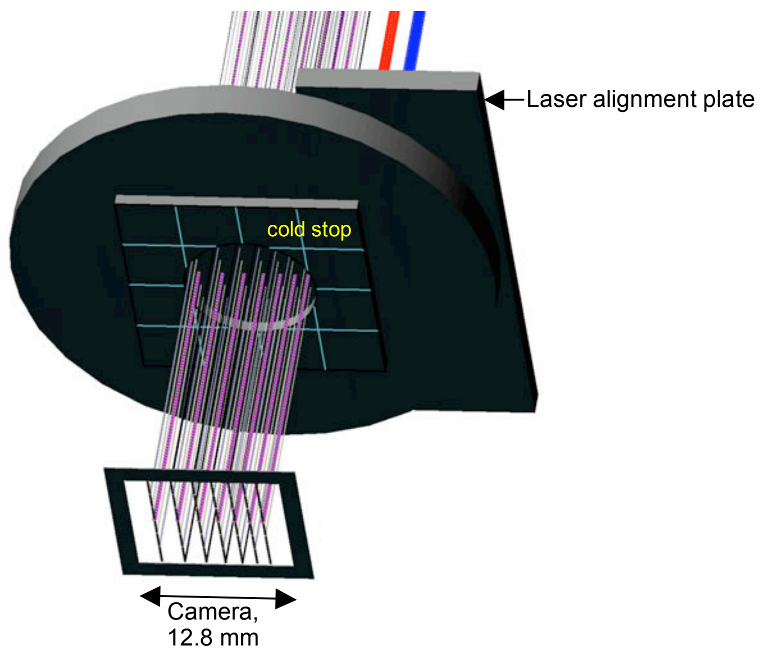

Fig.7. Perspective view of that shown in Figure 6, looking from IR camera towards the stop. The circular cold stop is a permanent component to the IR camera and it will clip light at the edges of the wavelength range.

4. ADJUSTING THE WAVELENGTH SPREAD

It may be necessary to change the wavelength spread presented to the IR camera. This spectrometer can be adjusted for different spectral ranges. By rotating the right-angle prism, changing the distance from the right-angle prism to the second parabolic mirror, and rotating this parabolic mirror, the wavelength spread can be adjusted as shown in Figure 8a and 8b. In this example, red HeNe and doubled Nd:YAG lasers were used for alignment. The 1300-nm wavelength was pointed to the center of the second parabolic mirror. The distance from the second parabolic mirror to the IR camera does not have to change.

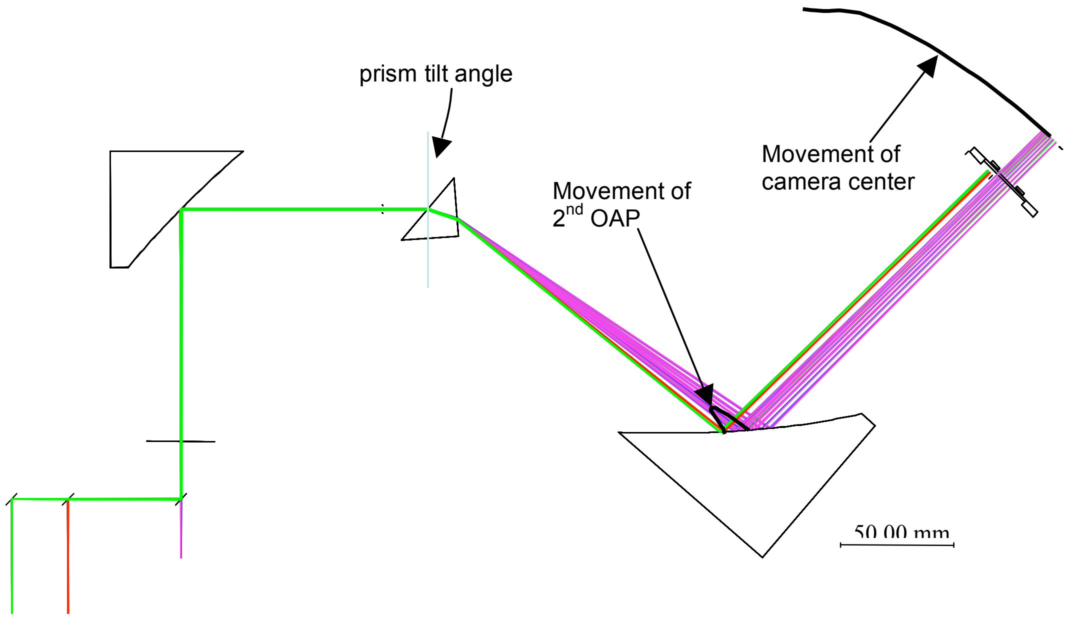

Fig.8a. The spectrum of 1500–4500 nm is spread to 7.85 mm at the IR camera. 3000 nm is centered on the second parabolic mirror.

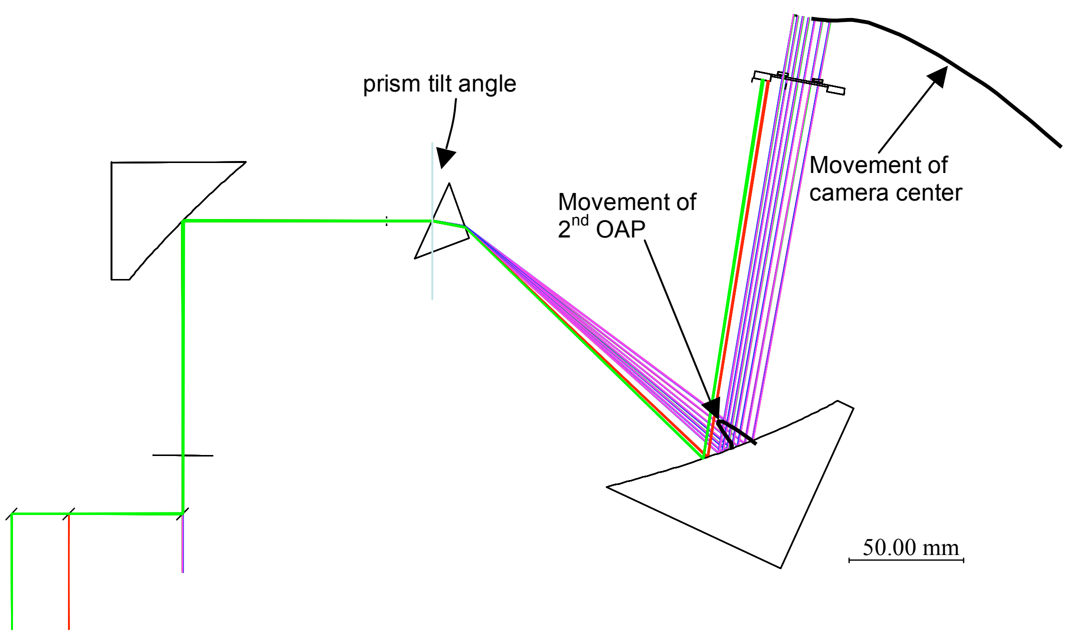

Fig.8b. The spectrum of 1500–4500 nm is spread to 16.20 mm at the IR camera. 3000 nm is centered on the second parabolic mirror.

Notice that for both orientations in Figure 8a and 8b, the light remains collimated going into the IR camera, but the movements of the prism and the second parabolic mirror are unusual. The prism is allowed to pivot about the center of its front face. In Figure 8a, the light is parallel to the OAP base. In Figure 8b, the light is no longer parallel to this base. These movements are graphed in Figure 9. Remember that each wavelength reflects off a slightly different curvature on the second OAP. The optical lens design program balances this curvature variation with the rotations. The total rotation of the prism is 15.98 degrees. The total rotation of the camera is 18.71 degrees. When these tilting operations are performed on the prism or parabolic mirror, the wavelength range must be recalibrated before an accurate spectra image is collected. Convenient, inexpensive calibration sources are provided by 1300-nm and 1500-nm pulsed laser diodes. Polystyrene filtered blackbody emissions have also been used as a means to test the resolution of this IR spectrometer.

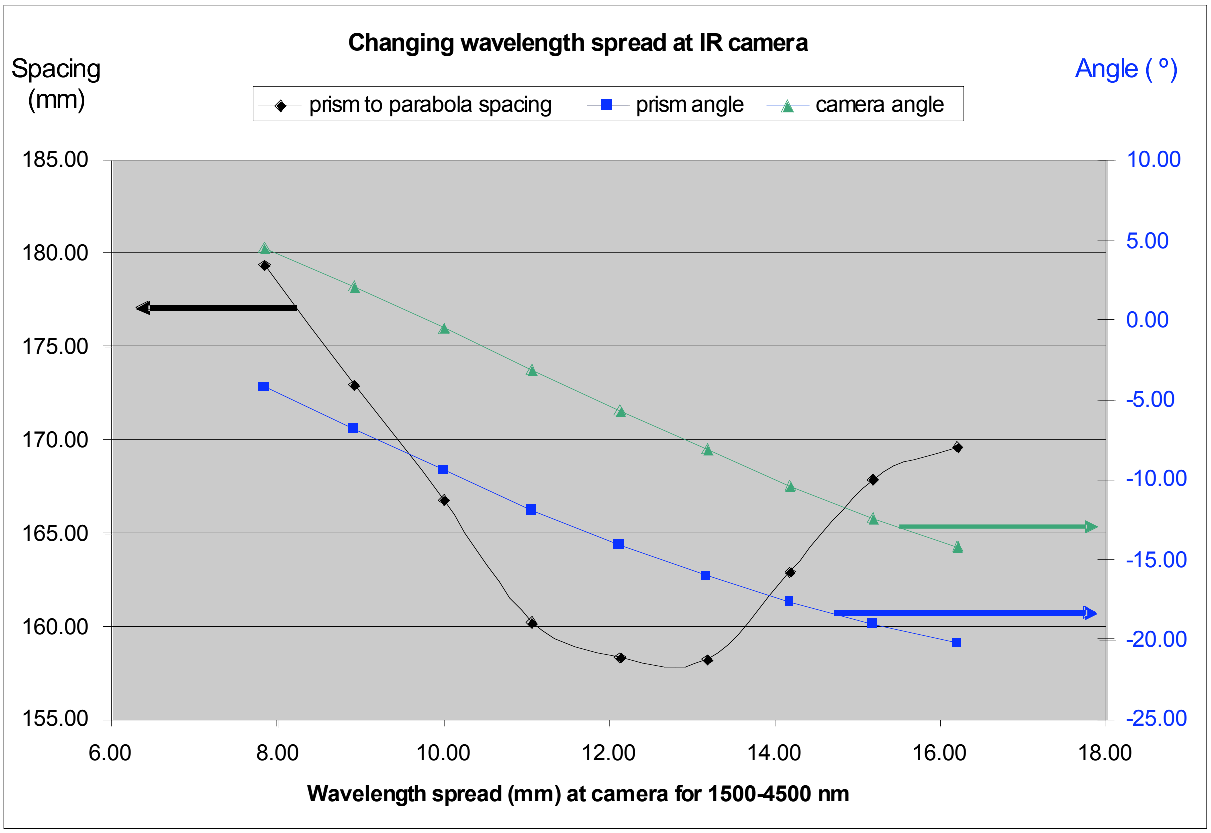

Fig. 9. The tilting of the prism and the spacing of the prism to second parabola (shown in Figure 8) are plotted. The spacing is from the front of the right angle prism to the middle of the second parabolic mirror.

5. ADJUSTING THE LIGHT SOURCE NA

The previous analysis used light from the NSLS. This light is nearly diffraction limited. What happens when gathering light from a diverging light source? Analysis was done to bracket acceptable amounts of divergence versus wavelength resolution. Figure 10 is an example of light emitted off a target with a numerical aperture (NA) of 0.02. A pair of entrance slits would be needed to define both the light emitted from the source as well as its angular spread.

The different wavelengths are still collimated entering into the camera. But, the tilted image plane is now evident.[2] The different wavelengths will spread at the camera and a loss of wavelength resolution will result. This spreading is shown in Figure 11. If one could accurately place the IR camera where the tilted image plane is, better resolution than shown in Figure 11 would result. Thus, this spectrometer is only useful for examining collimated light sources, but it can be operated over broad wavelengths.

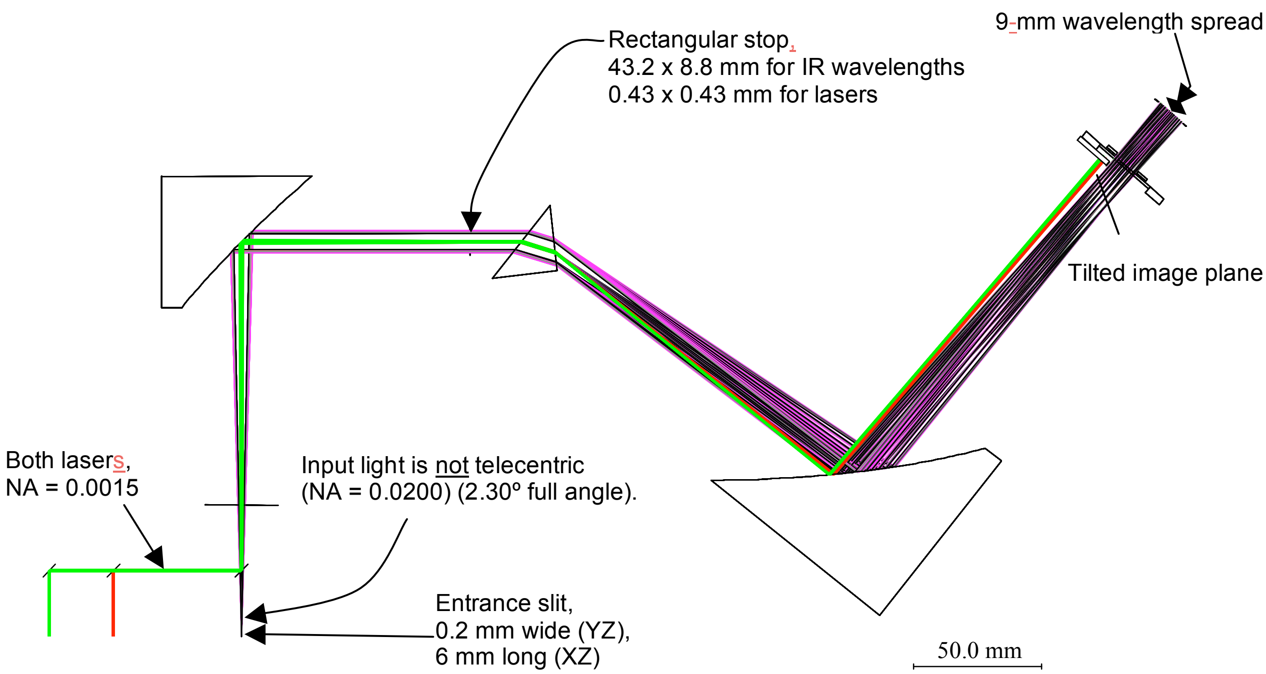

Fig. 10. Increasing the NA of the light source.

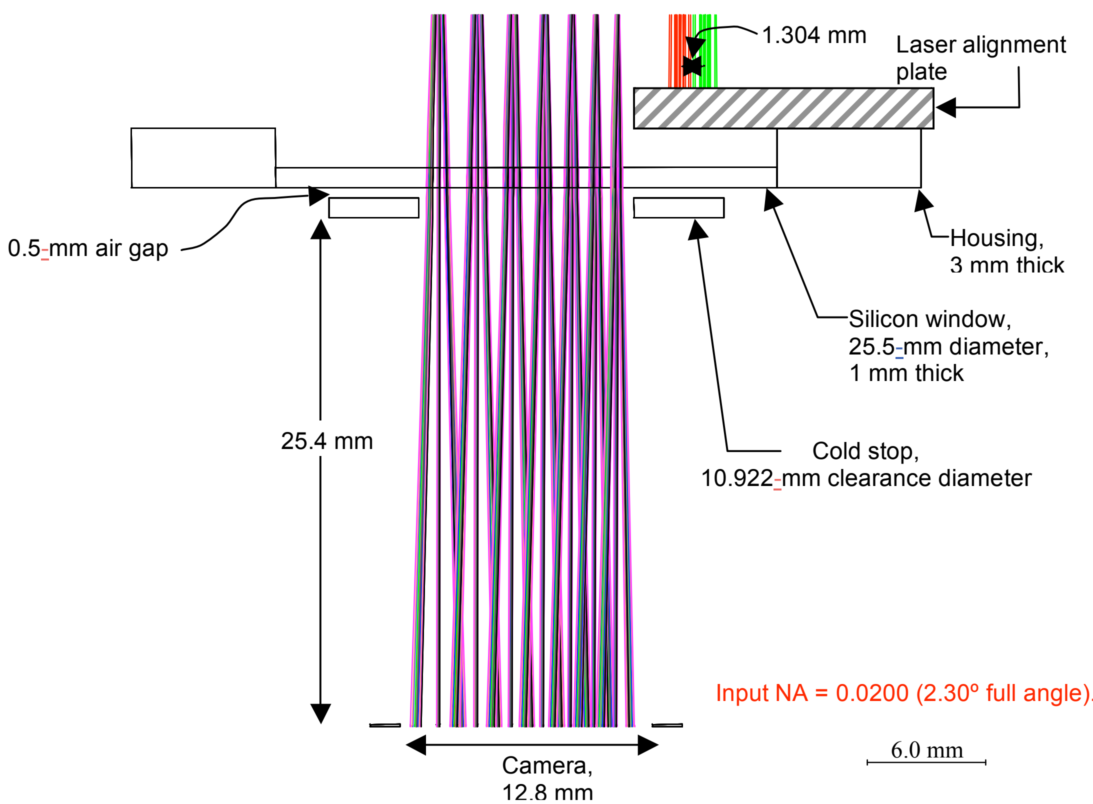

Fig. 11. Increasing the NA of the light source will cause the wavelengths to merge, resulting in loss of wavelength resolution.

6. SUMMARY

During our first spectra campaign at the Brookhaven NSLS, we were light-starved. Therefore, the next version of the interferometer will use a cylindrical mirror after the parabolic relay system to collapse the light onto the camera. Light will be collapsed along the spatial dimension so as not to affect the wavelength dimension.

This new IR spectrometer provides real time spectral measurements and broad wavelength coverage (1500–4500 nm). A two-dimensional gated IR detector array enables spectral analysis along a line profile of the target source light. The limit of the wavelength resolution depends on the divergence of the source light. Once calibrated, the wavelength spectrum should not drift on the IR camera sensor. Two alignment lasers provide visible confirmation of the spectral calibration and alignment. There are no scanning components during the spectra collection. Because the light is collimated at the camera, the camera positioning along the optical axis has loose tolerances. The optical design of the spectrometer is such that spectra can be collected without having to move or adjust any system components. This spectrometer is compatible with existing pyrometry diagnostics.

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