Zoom System for Coherent Imaging with No Moving Lens Groups

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ABSTRACT

Current variable image magnification methods present problematic issues for high precision metrology instruments. This paper describes a novel approach to providing variable system magnification while avoiding those shortcomings.
An optical zoom generally has multiple lens groups moving in concert to simultaneously adjust the effective focal length and maintain focus. Inevitably, the motion of the elements results in image drift and small variations in focus over the zoom range. An alternate approach using turreted fixed focal length lenses can have higher image quality but still suffers from image drift unless great care is taken in alignment of the individual lenses.
The variable-zoom method presented has a detector array with at least M*p pixels in each axis, where M is the maximum magnification and p x p is the size of the image array at each zoom. Pixels are binned based on the current magnification such that the final image size at each zoom magnification has a constant pixel array size. The fixed focal length imaging lens utilizes a variable aperture stop which is adjusted to maintain diffraction limited resolution. At low magnification the lens has a large field but requires lower resolution. As magnification increases the variable stop increases in size resulting in a smaller diffraction limited spot over a smaller FoV. The optical system can be much less complex than a traditional zoom and because there are no moving lenses, the image does not drift on the detector and there is no focal shift as the magnification changes.

Keywords: Phase-shifting interferometer, optical zoom,

1. INTRODUCTION

Early commercial laser interferometers lacked any zoom system. These systems utilized relatively low-resolution Vidicon cameras, which were the only detectors available at a reasonable cost at the time. With only about 300 lines of resolution, attempting to measure small optics with a 100 mm or 150 mm aperture interferometer resulted in very low resolution on the test surface.

The value in increasing the system magnification to test smaller parts with reasonable data density was quickly recognized. First, test surfaces that significantly underfilled the early low-resolution detectors lacked sufficient pixel density for a reasonable measurement. Including a zoom system allowed a single instrument to provide metrology capability for a wide range of test surface dimensions. Secondly, increased resolution helped with evaluation of the higher spatial frequency components on the surface allowing measurement of surface waviness/mid-spatial frequencies. There has been increasing demand for mid-spatial frequencies specification within the optical fabrication industry in recent years.

Modern Phase Shifting Interferometry (PSI) metrology instruments therefore often incorporate zoom options to increase the system magnification. To realize an improvement in metrology capability, it is critical that a zoom system must also improve both the optical resolution *and* sampling frequency at the surface under test. The term ‘zoom’ can be ambiguous; We’ll be using a generous working definition of the term zoom as any system that alters the Field of View (FoV) and resolution of the instrument as observed by the operator.

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Optics and Photonics for Advanced Dimensional Metrology III, edited by Peter J. de Groot, Felipe Guzman, Pascal Picart, Proc. of SPIE Vol. 12997, 129970A ·
 · 0277-786X · doi: 10.1117/12.3020562

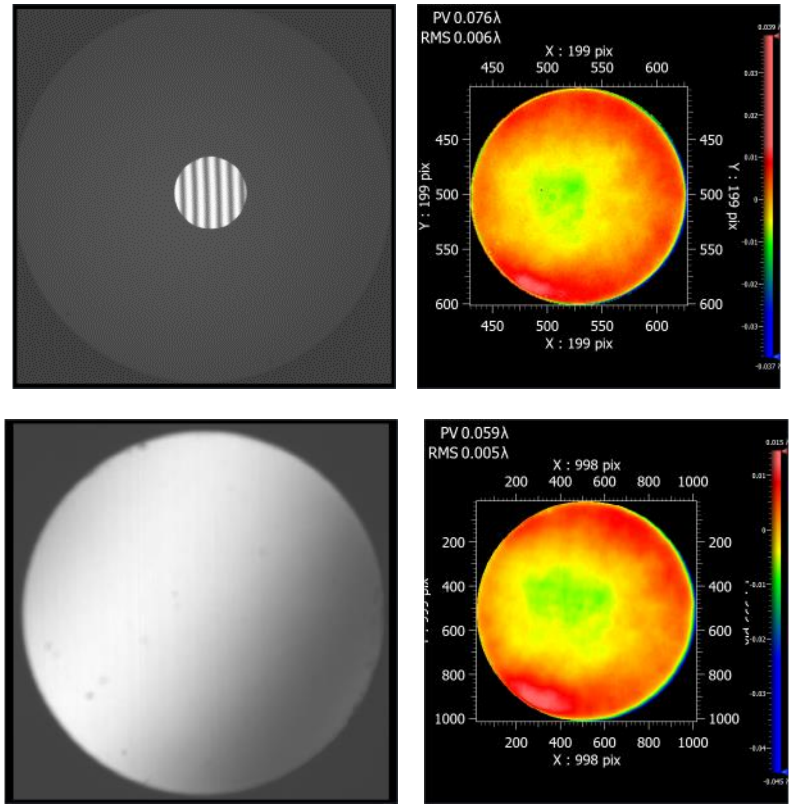

Figure 1. Interferogram and resulting phase map for small (~1") optic which subtends ~200 pixels at 1x system zoom (top row). When the system is zoomed by 5x, the surface subtends 1000 pixels (bottom row).

2. MAGNIFICATION IN COMMERCIAL PSI INSTRUMENTS

Almost all commercial interferometer systems implement a double telecentric optical system to form a reduced size primary image approximately sized for available sensors. The demagnification of the double telecentric optical system is set by the ratio of the ocular (the lens proximate to the image) focal length to the collimator (the lens at the input of the interferometer) focal length. The image is either projected directly onto the sensor or in the case of some systems passed through additional optics to adjust or vary the image size. For convenience, we will define the system demagnification which matches the aperture of the interferometer to the size of the sensor as an image magnification of 1. An example of a Fizeau interferometer with this configuration is shown in Figure 2.

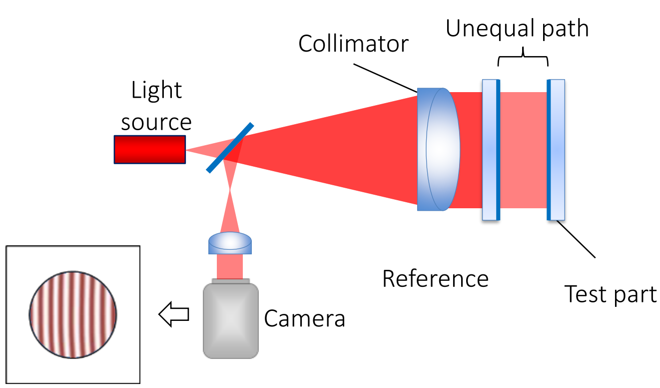

Figure 2: Layout of Fizeau Interferometer.

The input aperture size can be changed using two common methods. A smaller or larger collimator can be built into the interferometer to create a system with a new base demagnification. Common sizes for collimators in interferometers vary from 10 mm to 300mm. Another alternative is to add external telecentric optics in the form of a beam expander or beam compressor. These external optical systems typically change a 100 mm aperture to sizes ranging from 25 mm to 800mm. These methods change the base aperture size of the instrument and define the demagnification that the user typically refers to as 1x zoom.

This paper focuses on the other end of the imaging train at the ocular, which produces the image on the detector. The following sections will go into detail regarding the various methods to vary the practical system magnification. We look briefly at their history and the problem that each solves. It should be observed that each solution implemented is the most appropriate given the system requirements, cost, and technology available at the time it was implemented. As this was a problem to solve even at the very birth of commercial interferometry, the following sections reflect an unbroken thread of technological development to improve the resolution of commercial PSI instruments, making the best use of available technology of the time.

Zoom Lens Considerations in Phase Shifting Interferometry

There are several considerations when designing a zoom system for a PSI interferometer:

The Fizeau architecture, which is typical of commercial PSI instruments, requires a long coherence length source, such as a laser. Due to the long coherence, scattering surface defects act as a point source that can interfere with the measurement beam of the instrument. This results in a classic bullseye pattern for surface digs, material inclusions, and dust accumulated on the various optics within the instrument. Similarly, surface texture causes scattering and produces a quasi-random phase variation, called coherent noise, in the measurement. Coherent noise limits the instrument's ability to accurately measure high spatial resolution content on the test surface.

To mitigate the impact of coherent noise and artifacts, high quality optics that are low-roughness and low surface imperfection must be used. The requirements on the quality of optics increases the cost to manufacture them, so there is a larger-than-usual incentive for the designer to minimize the number of lenses in the design. Alternatively, the spatial coherence of the measurement beam may be broken in the common-path portion of the instrument, after test and reference beams have recombined. This would allow for a more complex imaging configuration without inducing coherent noise or artifacts.

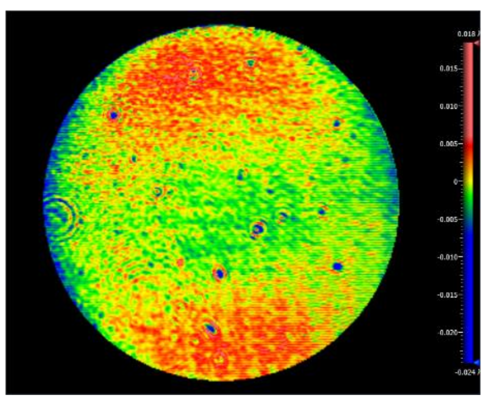

Figure 3. PSI phase map with many coherent artifacts (bullseye pattern) from lens surface defects and coherent noise.

As mentioned in the previous section, it is critical that the optical design supports an increase in optical resolution as the spatial sampling frequency of the test surface is increased. Otherwise, the image size may increase on the detector, but the resolution will be limited by the optical resolution of the system. In the other direction, if the optical resolution exceeds the sampling frequency, then aliasing of the fringes will occur. This means that we should match the optical cutoff frequency to the detector Nyquist frequency and achieve diffraction limited performance for all zoom configurations.

Existing zoom systems with moving lenses exhibit some amount of image shift when changing zooms. Due to the manufacturing and assembly tolerances, as well as the optical design of the system, this shift can never be completely eliminated as long as the lenses are allowed to move. The shift occurs along the optical axis of the system, causing a variation in the focus plane position and requiring an adjustment to system focus after changing zoom. This shift also occurs perpendicular to the optical axis, changing the position of the center of the image on the detector. For precision metrology instruments, such as phase-shifting interferometers, it's desirable to minimize this effect.

3. SELECTED ZOOM SYSTEMS IN PSI INTERFEROMETRY

Digital Zoom

One common way to change the FoV of an optical system is to use digital zoom. This is familiar to anyone that has used point-and-shoot or cell phone cameras. There's a common practice within that industry of including a digital zoom factor with any available optical zoom and referring to the product as 'total zoom' or similar. Within the field of optical design, it's well-understood that digital zoom is not a zoom at all, but instead a crop of the image.

The crop can happen at the sensor before the image is captured, such as with digital cameras, or it can be applied at the display. One can simply crop a picture after it is captured for the same effect of digital zoom. Because there is no change to the imaging system or spatial sampling at the detector, the Instrument Transfer Function (ITF) is not improved by this function.

Figure 4. Demonstration of the familiar concept of digital zoom. Image of cute cat (left) and digitally zoomed region (right) are both 300 x 300 pixels, but the digitally zoomed section does not improve the resolution in the region of interest. © 2024 Nate Austin

While digital zoom does not provide additional information, it does have some utility within commercial PSI metrology system. High-resolution cameras capture more pixels than can be displayed on a full HD (i.e. 1080p) monitor, it is necessary to employ some form of digital zoom to display the data set at its native resolution. This functionality is generally available in analysis software packages, such as Zygo Mx, via a scroll wheel or similar UI control.

Continuous Zoom

By far the most common optical zoom configuration in commercial interferometers (and other non-interferometric applications) is the continuous zoom. This type of zoom dates to the turn of the 20th century and is what is generally referred to by the strictest definition of 'zoom lens'. The effective focal length of the lens is increased via a moving lens or group of lenses to increase the overall magnification of the system while another lens or group of lenses moves in concert to compensate for the focus shift to maintain sharp focus on the image plane throughout the range of zoom motion.

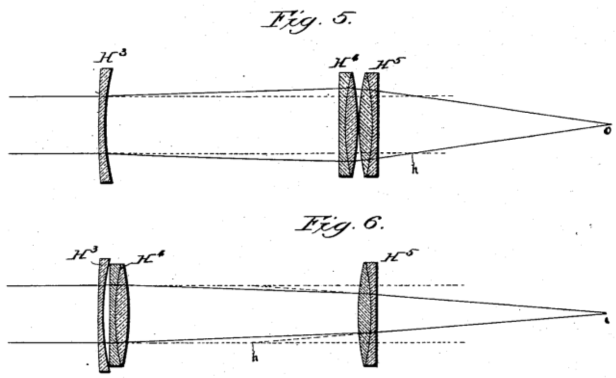

Figure 5: Earliest implementation of continuous zoom showing a true zoom in which effective focal length is changed while the focus position remains fixed (US Patent No. 696788, 1902).

Zygo's GPI Mark series of interferometers implemented a 6:1 ratio continuous zoom lens into the imaging system (Zygo Corporation, 1980). This was the only type of zoom available for many years and was adequate given the technology and customer demands of the time. The first available CCD detector used in the Zygo Mark III interferometer only had 100 x 100 pixels. The 6x zoom feature made the interferometer useful for measuring parts down to about 5 mm in diameter. Over the years the detector resolution in the Zygo Mark and then GPI systems slowly increased first to 256 x 256 then to 512 x 512 and now to over 1k x 1k. The same optical zoom system was used to allow users to fill the detector and produce useful image sizes.

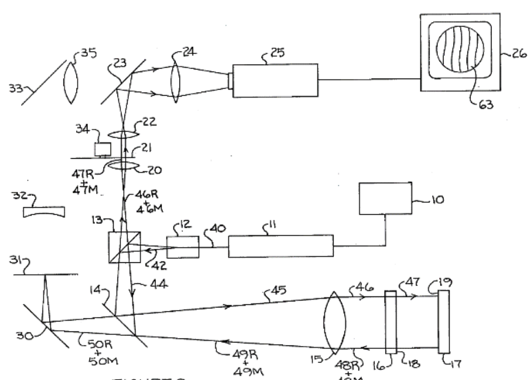

Figure 6: Internal layout of Interferometer with continuous zoom (US Patent No. 4201473, 1980). The portion from Item 21 to 25 is the incoherent imaging leg utilizing continuous zoom lens, Item 24.

This zoom configuration is extremely popular for a variety of applications. As such, they are readily available and affordable and offer an excellent range of zoom. PSI interferometers are very sensitive to the quality of the optics within the coherent portion of the system. For the same reasons that continuous zoom lenses are affordable and readily available, they are not practical for coherent imaging. While they are more than adequate for incoherent imaging, the surface imperfections on the numerous surfaces would yield coherent noise artifacts that are not acceptable for a commercial product. The only way to reasonably implement this solution is within an incoherent imaging leg of the interferometer. Note that the coherent imaging portion consisting of the collimator and the ocular form a primary image on a spinning ground glass diffuser disc. The ground diffuser disc breaks the coherence, so that the incoherent primary image created on the ground glass surface can then be relayed to the camera via commercial zoom lens relay system.

In addition to the coherence limitations, utilizing the continuous zoom lens significantly increases the size and weight of the instrument. Fully coherent imaging could be realized if the detector were placed at the primary image location.

Discrete Zoom Turret

A discrete zoom turret uses multiple zoom lenses, each with a fixed focal length, to switch system magnification. The lenses are moved in and out of the optical train via a mechanical turret. Each zoom lens is designed to support full resolution imaging at each magnification. The discrete lenses are simpler with fewer elements and no internal moving parts making them more compatible with coherent imaging. The discrete turret can be utilized in systems that are fully coherent and can be utilized to enable functions that require coherent imaging.

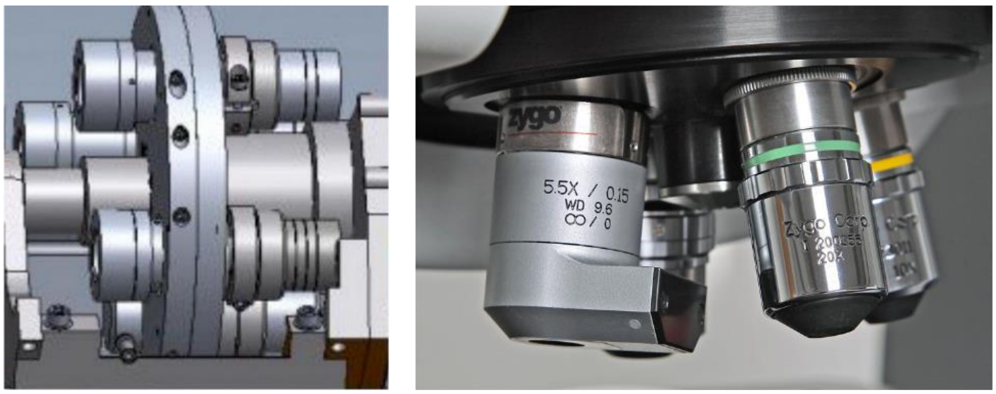

Figure 7. CAD model of motorized turret with multiple zoom relays in PSI interferometer[3] (left) and analogous motorized turret with interference objectives on CSI optical profiler[4].

However, each discrete zoom lens within the turret requires high quality components, increasing the cost. Each of the lenses on the turret must be aligned with respect to each other minimize the shift in focus and image location when the zoom turret is changed. This complex system requires significant labor to align, and those errors can never be truly eliminated.

High-Definition Interferometer Systems

With the advancement of sensor manufacturing, high-resolution detectors have become available. For example, Zygo's HDX interferometer boasts a full 3.3k x 3.3k resolution optical system and achieves diffraction-limited performance over the entire field of view of the 4" aperture. To achieve this resolution over the full aperture requires many optical elements all very precisely aligned and all quite large in diameter compared to an interferometer with lower resolution. The result is a very high-performance imaging system at an equally high cost.

While a high-resolution PSI instrument does not meet our definition of a zoom, it does provide an increase in resolution to the user over previously available systems. When compared to a typical ~1k x 1k system, it provides the same outcome as a 3x zoom over the field. However, most applications don't require such resolution over the full field.

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[3] https://store.zygo.com/3-position-motorized-discrete-zoom-turret
[4] https://www.zygo.com/products/metrology-systems/3d-optical-profilers/key-features/profiler-objectives

4. A NOVEL ZOOM SYSTEM WITH NO MOVING LENSES

To address the drawbacks of previous optical zoom systems, a new, patented zoom was developed and introduced here. For the majority PSI metrology applications, a system resolution of approximately 1k x 1k pixels is adequate. This zoom system is specifically designed for use within that market space.

Description of the Zoom System

This novel zoom system has 3 main components. Refer to Figure 8 for item numbers:

1) A high-resolution detector (Item 145)
2) A fixed-focus imaging lens (Item 140)
3) An adjustable aperture stop (Item 135)

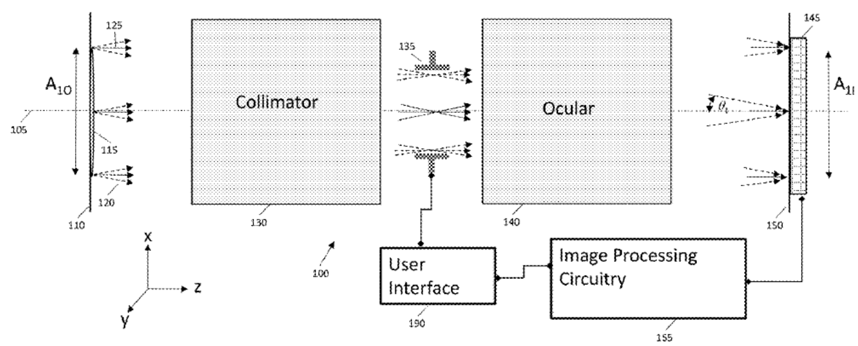

Figure 8: Block diagram of this novel zoom system (US Patent No. 11841548, 2023)

When the zoom is changed, 3 operations occur:

1) Acquisition area is adjusted to desired field of view (FoV)
2) Aperture stop diameter adjusts, increasing point-spread to maintain number of resolved points across FoV (e.g. 1k x 1k)
3) Acquired data is re-sampled to match optical resolution (e.g. 1k x 1k)

As an example, we could utilize a high-resolution detector with 3k x 3k pixels. At 1x zoom the ocular is designed to cover the full field of view of the collimator and it is designed such that the optical quality supports a uniform resolution of 1k x 1k pixels over the full field of view. This is done through both the design of the lenses and by proper sizing of the aperture stop. At 1x zoom the sensor is binned 3x3 to produce a 1k x 1k pixel image. Then for 3x zoom the aperture stop is opened by 3x compared to the full-field image and only the central 1k x 1k pixels are utilized.

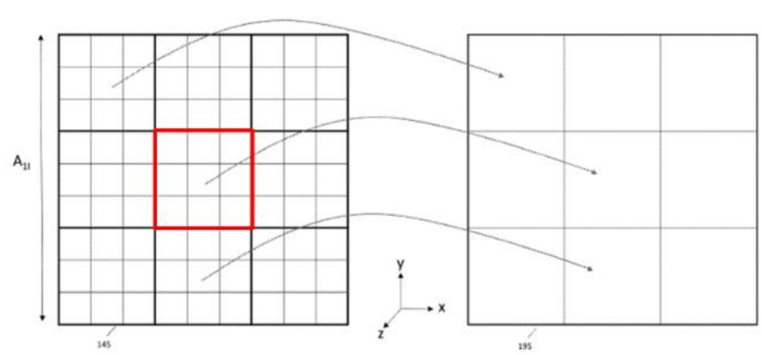

Figure 9. Demonstrating pixel binning to maintain number of acquired detector elements (US Patent No. 11841548, 2023). The red square shows 3x FoV with each pixel fully resolved.

The optical design of the ocular is the key to this novel zoom. It is designed to be diffraction limited as the stop size increases but only over a decreasing field of view. The design for this ocular is considerably simpler and the lenses are smaller than an ocular designed for 3k x 3k-pixel resolution over the full field such as the ocular used in the Zygo HDX system. In other words, we couple a high-resolution detector with an optical system designed for a 1k x 1k resolution image at each binned FoV and an adjustable aperture stop to create an effective zoom system without the need for moving lenses. As the detector elements are binned for reduced resolution and a larger field of view, the aperture size is reduced so the optical cutoff frequency matches the Nyquist frequency of the detector. Thus, the system is diffraction-limited for all zoom configurations and there is no aliasing.

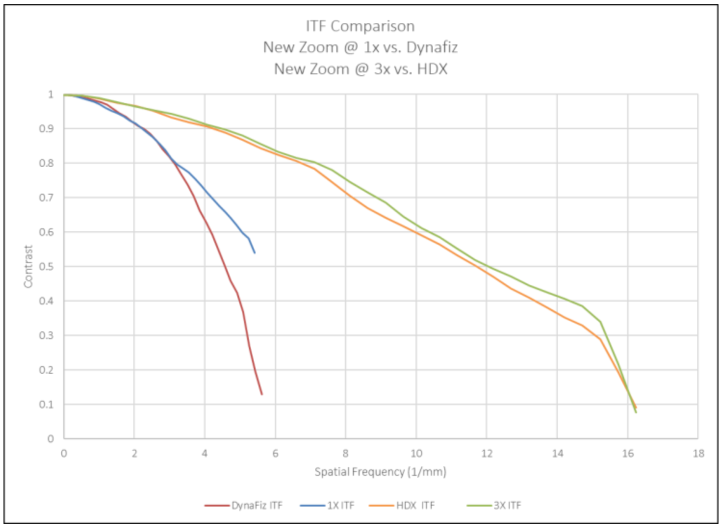

Figure 10. Here we compare the ITF of our new zoom prototype with existing interferometer systems. The blue and green lines represent the binned full-field image and the 3x field at full pixel resolution, respectively.

Advantages of the Novel Zoom Method

The patented zoom system offers the user several important advantages:

Image Stability

Because the only moving optical component is a variable sized stop, the image is completely stationary when changing magnification and there is no image shift with magnification change. There is also no image size change on the detector. This means that a calibration file applied at 1x works equally well at any available magnification. Also, because the full-size image is always present on the sensor "behind the scenes" the software can always validate the size and registration of the reference file.

Stable and accurate lateral calibration

Because the optical elements are stationary the image does not move on the detector when magnification is changed. Thus, the instrument can be laterally calibrated at the factory for the full field image at 1x. This calibrates the underlying camera pixel sizes, which do not change with zoom. Therefore, all three zooms are automatically calibrated to a high degree of precision.

Focus Stability

Again, because the optical elements are stationary and only the stop is moving there is zero focus shift with zoom. If the user wants to critically focus the cavity, they can switch to a high zoom magnification, carefully focus the image and then switch back to 1x and take data with a much more precise focus.

Improved light sensitivity

If implemented in a binning mode, the full-field, 1x camera mode, the system will be able to sum detector counts for an improvement in the light sensitivity. This could be used in situations where the instrument is otherwise light-starved to improve the signal-to-noise ratio and, therefore, decrease the measurement uncertainty.

Cost

This novel zoom solution is more cost-effective than other coherent zoom options that maintain diffraction limited performance across all magnifications.

- The turret-mounted zoom has many more high-quality optical elements, requiring any entire zoom relay assembly for each discrete magnification. It requires precision mechanics to switch between zooms repeatably and precision alignment during alignment.
- The high-resolution interferometer requires significant improvement of optical performance to yield diffraction limited performance across the entire field. This means additional tightly toleranced elements and additional alignment during assembly.

By reducing the system cost, the interferometer will be accessible to more customers, increasing the market size for products utilizing this technology.

5. SUMMARY AND CONCLUSION

In this paper we've presented several useful zoom configurations for commercial interferometry instruments as well as the primary drawbacks of each. We've gone on to present a novel type of zoom configuration and expound on methods by which it mitigates many of those drawbacks when used for moderate resolution interferometer systems. The primary benefit is the stability of the image on the detector due to a lack of moving elements within the system.

6. REFERENCES

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