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Peter J. de Groot, James F. Biegen, "Interference microscope objectives for wide-field areal surface topography measurements," *Opt. Eng.* **55**(7), 074110 (2016), doi: 10.1117/1.OE.55.7.074110.

Optical Engineering 55(7), 074110 (July 2016)

Interference microscope objectives for wide-field areal surface topography measurements

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Abstract. We propose a type of interference objective that extends the range of application for flexible microscope platforms to larger fields of view. The objective comprises a beamsplitter plate and a partially transparent reference mirror arranged coaxially with the objective lens system. The coaxial plates are slightly tilted to direct unwanted reflections outside of the imaging pupil aperture, providing high fringe contrast with spatially extended white-light illumination. Examples include a turret-mountable 1.4× magnification objective parfocal with high-magnification objectives up to 100× and a dovetail mount 0.5× objective with a 34 × 34 mm field. This design is a practical alternative to the classical Michelson and Mirau type objectives for low magnifications. [DOI: 10.1117/1.OE.55.7.074110]

Keywords: interference microscopy; microscope objective; white-light interferometry; coherence scanning.

Paper 160732P received May 10, 2016; accepted for publication Jun. 29, 2016; published online Jul. 22, 2016.

1 Introduction

Surface metrology on the microscopic scale is an essential step in the precision manufacturing and production of many modern products. Functional characteristics of parts ranging from diesel fuel injectors to patterned semiconductor wafers require three-dimensional (3-D) surface topography measurements with height resolution on the nanometer scale, often using interferometric techniques. Although part sizes for "microscopy" are subject to interpretation, most often the field of view of microscopes extend from ~0.1- to 10-mm square. This range encompasses a large number of parts and feature sizes. There is nonetheless a continuing interest in enlarging the field of view beyond the usual limits of microscope objectives while preserving the flexibility, functionality, and precision of a 3-D interference microscope. The increasing availability of high-speed, large-format cameras enables this expansion while preserving a sampling density that takes the most advantage of the available optical resolution.

In reviewing the state of the art, we find that obstacles to increasing field of view are the size, weight, and form factor of classical interference objectives. This present work seeks to overcome these obstacles with a new class of interference objective that is better suited to low magnifications than the more established designs. We present the concept underlying the design followed by example implementations and applications illustrating the benefits of the new objective.

2 Current State of the Art

2.1 *Microscopes for Interferometry*

Interference microscopes for areal surface structure analysis typically comprise infinity-corrected optical systems, electronic cameras, and specialized objectives that are actually compact interferometers. A familiar configuration is a mechanically robust platform with turreted interference objectives covering a range of focal lengths and corresponding magnifications. The light source most often is a light-emitting diode (LED) or a color-filtered thermal source such as a halogen bulb. Köhler illumination is also common, with optics arranged to fill the objective pupil so as to achieve a good approximation of spatially incoherent light and to extend the lateral resolution limit to the theoretical maximum achievable with each objective. A final component of importance is a mechanical focus-scanning mechanism that enables phase-shifting interferometry (PSI) and coherence scanning interferometry (CSI) by computer-controlled modulation of the optical path difference in the interferometer. Expected noise levels in final surface height data are $<0.1\ \mathrm{nm}/\sqrt{\mathrm{Hz}}$ in PSI mode.[1] Several comprehensive review articles detail the capabilities, measurement principles, and applications of interference microscopes.[2–5]

2.2 *Classical Interference Objectives*

With the exception of Fizeau-type objectives for laser-based systems,[6] interference objectives require an equal-path geometry carefully balanced for dispersion and chromatic aberration. This is especially true for microscopes designed for CSI data acquisition, which almost by definition involves diffuse, broad spectral bandwidth light sources with coherence lengths of only a few microns. For half a century, interference microscope objectives have been the Linnik, Mirau, or the Michelson type, with the occasional specialized design for unique applications.

The Linnik interferometer is the combination of two conventional microscope objectives, one for the reference path and the other for the imaging path, usually with a cube beamsplitter.[7,8] This configuration is attractive for its large working distance at short focal lengths, e.g., 2 mm for a 100× magnification, when using a 200 mm focal length (1×) tube lens for the final imaging onto the camera. The

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Linnik design requires carefully selected objectives for balanced dispersion and compensated aberrations. Although Linnik objectives played a central historical role in the development of interference microscopy and are still commercially available today, the cost and complexity of such objectives restrict their use to specialized applications.

Mirau[9] invented his design in the 1940s, which today is the preferred type for high magnifications. The Mirau objective shown in Fig. 1(a) has the advantage of coaxial lens, beamsplitter, and reference mirror and an inherently compact package. Assuming that the beamsplitter and reference mirror are cut from the same glass, the symmetry of this configuration brings the reference and object surfaces simultaneously into precise focus at the position of zero optical path difference, with minimal dispersion imbalance and high fringe contrast. The small reference mirror obscures the light path; however, if the pupil is filled with spatially extended illumination, a high numerical aperture (NA) accommodates the central obscuration. Typically, these objectives range in magnification from 10× to 100×, with the field of view of a 20× objective ∼0.45-mm square for a 1× tube lens.

At magnifications lower than 10× and correspondingly smaller NA values, the central obscuration of the classical Mirau type blocks too much of the light. One possible solution is to use polarizing elements to control the transmission through a partially transparent reference surface, in what is referred to as an unobscured Mirau objective.[10,11] However, the polarizing elements considerably complicate the design, making it more difficult to compensate dispersion and introducing sensitivity to polarization effects that are otherwise not relevant to the Mirau because of its circular symmetry.

The Michelson geometry of Fig. 1(b) has been the preferred solution for magnifications lower than 10×. This configuration comprises a conventional microscope lens, a beam-splitting cube prism, and a reference arm assembly orthogonal to the main axis of the objective. The design has origins in Sagnac's[12] proposal for interferometric texture measurement and was made popular as an interchangeable microscope objective by Watson and Sons in 1960s.[13] There is no central obscuration as in the Mirau type, allowing for smaller NA values and larger fields of view. However, for magnifications below 2×, the physical size of the Michelson design, with its prism and off-axis reference path, can be unwieldy. This is particularly the case if the desire is to mount the objective on a turret with other objectives of higher magnification. As a consequence, fields of view larger than 10 mm are often associated with Twyman Green[14–16] or other custom interferometer platforms that differ from the more flexible model of a microscope with interchangeable objectives.

3 New Type of Wide-Field Interference Objective

We consider here an objective design for interference microscopy, i.e., an attractive alternative to the classic Mirau and Michelson types for low magnifications. The wide-field objective shown in Figure 2 uses a pair of partially transparent plates, arranged coaxially with the objective lens. A front-surface reflection from the beamsplitter results in a reference beam that reflects from the back surface of the upper plate, resulting in matching glass thickness for the reference and measurement paths. The plates are positioned so as to achieve equal optical path difference when the object is in focus. Because the plates are partially transparent, there are several reflected beams that do not take part in the interference effect. A small tilt angle for both plates, from one to two degrees for the beamsplitter and twice that amount for the reference, directs these unwanted reflections off axis, where they are blocked by internal apertures, leaving only pure two-beam interference of high contrast (>70%) even in white light.[17,18]

Comparing to Fig. 1, the design resembles in some respects the Mirau geometry, with the important difference that there is no central obscuration—the reference plate is partially transparent and passes the illumination rays from the pupil to the object even when the NA approaches zero. There are no polarizing elements. Accommodating the tilted plates has little effect on imaging quality at NA values <0.1;

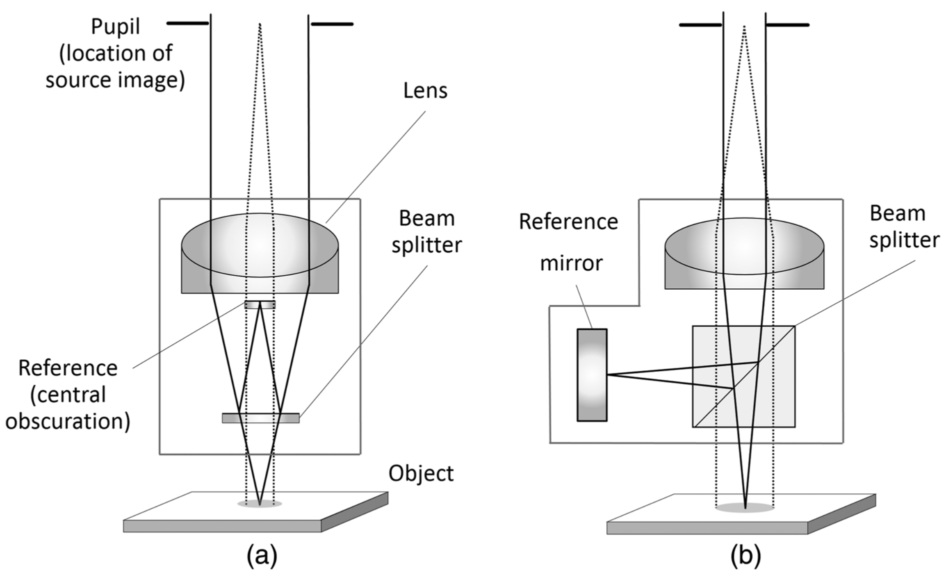

Fig. 1 Classical interference objectives in common use for 3-D surface microscopy. (a) Mirau objective with a small, coaxial reference surface that partially obscures the illumination and imaging light and (b) Michelson objective using a prism and a reference path orthogonal to the measurement path.

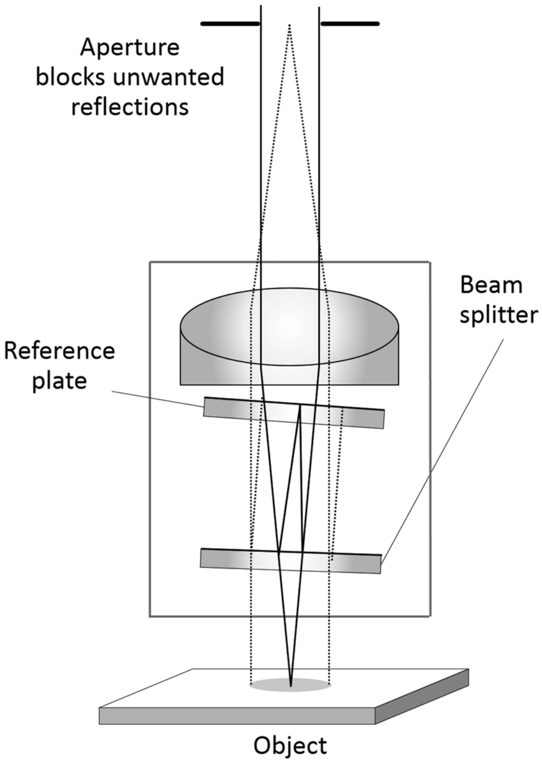

Fig. 2 New design for a wide-field objective with coaxial, partially transparent reference and beamsplitter plates. The plates are slightly tilted to reject unwanted reflections outside of the acceptance angle of low-NA objectives.

hence, the design is most attractive for large field of view applications, where the inherently compact and lightweight design is preferable to an oversized Michelson objective. Indeed, the concept was first developed for a 100-mm aperture interferometer operating with LED illumination for applications requiring the separation of the front and back surfaces of plane-parallel transparent plates.[19] The present work shows that the same idea is of practical value for interference microscopy, effectively extending the range of manageable apertures on a flexible platform for both roughness and surface texture.

4 Example Objectives and Applications

4.1 *Turret Mounted 1.4× Objective, Parfocal with Higher Magnifications*

Figure 3 shows a first example wide-field 1.4× interferometer assembled from a microscope objective lens and the tilted beamsplitter and semitransparent reference plates. The plates fit neatly between the lens and the sample, in a working space that is far too restrictive for a Michelson prism. This allows the complete objective to maintain the 60-mm parfocal length common to interference objectives from 5× to 100×.[20] The new objective is more compact than a 5.5× Michelson type (see Fig. 4) while providing a 17-mm diameter field of view—an image size unmatched by any commercially available objective with this parfocal length. Table 1 lists the technical specifications for this objective.

Figure 5 illustrates the range of magnification made possible by the 1.4× objective with a fixed 1× tube lens with

Fig. 3 Compact 1.4× interference objective based on a 144-mm focal length microscope objective and the configuration of Fig. 2.

Fig. 4 The 1.4× interferometer (to the right in the figure) mounted on a turret with parfocal 2.75× and 5.5× Michelson objectives and a 20× Mirau objective. These lenses all have the same 60-mm parfocal distance.

Table 1 Turret-mounted wide-field 1.4× objective.

Attribute	Specification
Field of view (0.5× tube lens, 1-MP camera)	12×12 mm (∅ 17 mm)
NA	0.04
Working distance	4 mm
Optical lateral resolution (sparrow)	7.13 μm
Parfocal length	60 mm
Focal length	144 mm
Measured fringe contrast (BK7 sample)	75%

minimal refocusing, using the objective turret. The images are for a lateral calibration sample having a variety of grid sizes. In the 1.4× image, the coarse grid has a 0.5-mm pitch, easily accommodated in the 6×6 mm field at 1× zoom. The finest grid, with a 0.03-mm pitch, is just barely resolved, but we can observe the overall form of the sample on a nanometer height scale. A motorized turret moves into

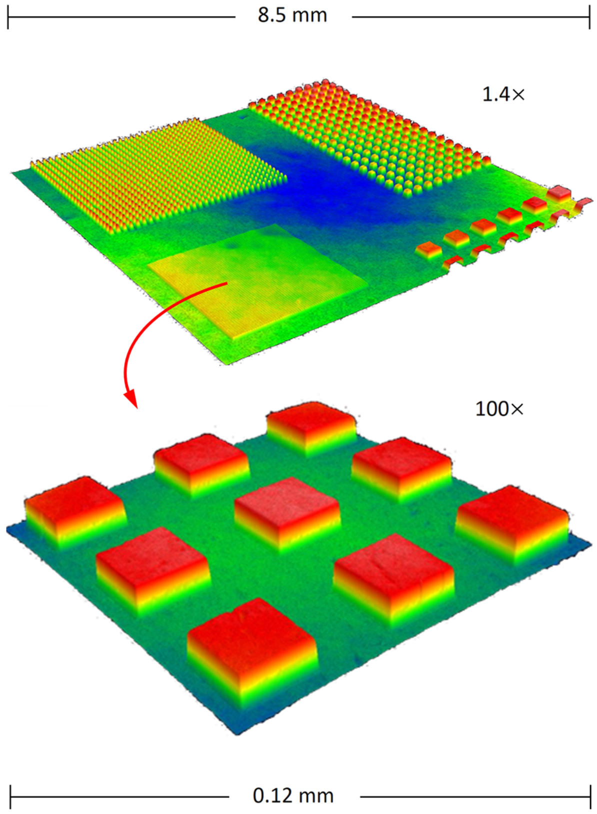

Fig. 5 Illustration of the dynamic range in field of view between two parfocal objectives mounted on the same turret: The new 1.4× (upper figure) and a Mirau 100× (lower figure). The tube lens in this example has a fixed 1× magnification. The feature height is 0.04 μm.

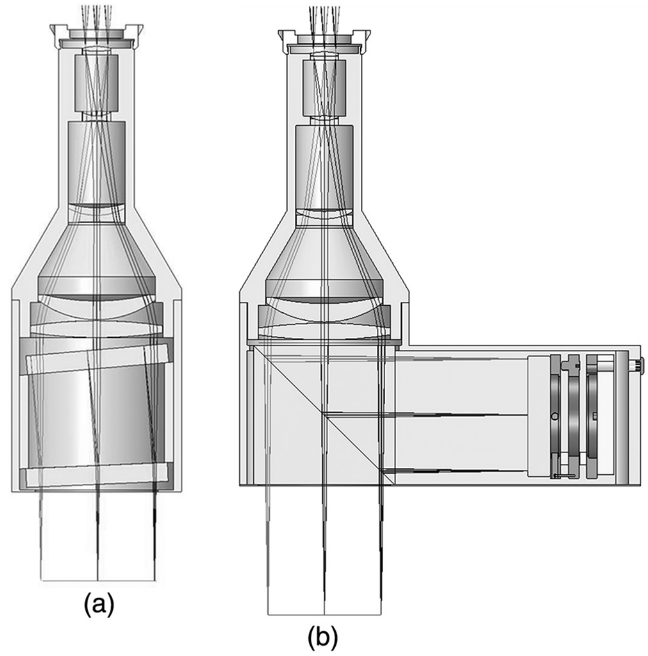

Fig. 6 Comparison of (a) the new wide-field and (b) the traditional Michelson geometries for a 0.5× interference objective. At low magnification and corresponding low NA, the new design is more compact and easier to handle.

place the 100× objective with a 0.083 × 0.083 mm field that images detail of the individual squares of the 0.03-mm pitch grating. This figure demonstrates the ability to easily switch between millimeter-scale form and micron-scale structure and texture using parfocal objectives. Software switchable tube lenses available on some systems further extend the range of field sizes, enabling system magnifications from 0.7× to 200× using 0.5× to 2× zoom settings, respectively. [Software selectable tube lenses (also referred to as zoom lenses) are available on the ZYGO Nexview™ and NewView™ 8300 interference microscopes].

Table 2 Dovetail-mounted wide-field 0.5× objective.

Attribute	Specification
Field of view (0.5× tube lens, 1-MP camera)	34 × 34 mm (∅ 48 mm)
NA	0.015
Working distance	50 mm
Optical lateral resolution (sparrow)	19 μm
Parfocal length	284 mm
Focal length	400 mm
Measured fringe contrast (BK7 sample)	79%

4.2 *Dovetail-Mount 0.5× lens*

It is reasonable to ask how large a field of view is achievable with the new design if we set aside the requirements of 60-mm parfocal distance. An answer is provided by a 0.5× lens for measuring large surface areas on a standard CSI microscope platform. An objective at this low magnification presents many challenges—the focal length is 400 mm, and the large field requires a beamsplitter with a clear aperture of 80 mm. Figure 6 shows the considerable advantages in size, weight, and manageability of the new design when compared with what would be the required in the Michelson geometry.

A 0.5× objective is now available commercially with a 48-mm diameter field of view when using a 0.5× (100-mm focal length) tube lens. Table 2 lists the technical specifications for this objective. The optical design achieves well-controlled lateral chromatic aberration <8 μm through the tilted beamsplitter and reference plates, and a distortion <0.1% over the full field at 0.015 NA. A dovetail mount allows for installing the objective interchangeably with objectives of other magnifications on a complete CSI system for both form and texture measurements. A megapixel camera provides lateral sampling of 32 μm over a 32 × 32 mm area.

A primary target application is the measurement of technical surfaces using CSI. Figure 7 shows the measurement result for a metal part having a ground, unpolished surface finish. The surface roughness is such that there are no continuous fringes visible in the instrument. The full 3-D image with 1 million data points requires only a few seconds to measure with CSI and the new 0.5× objective.

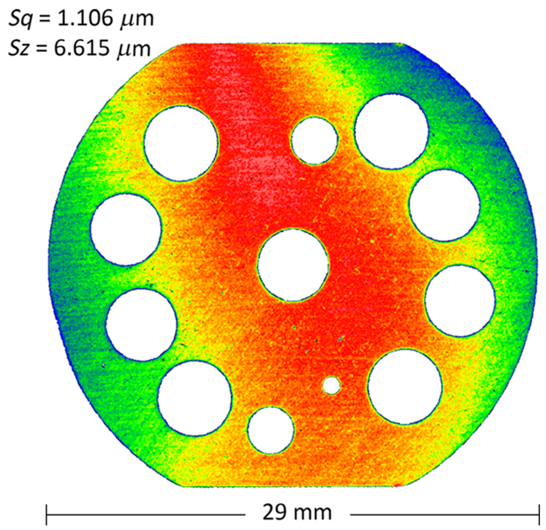

Fig. 7 False-color 3-D areal topography map of a machined fuel injector component, measured with one field of view using the new 0.5× objective.

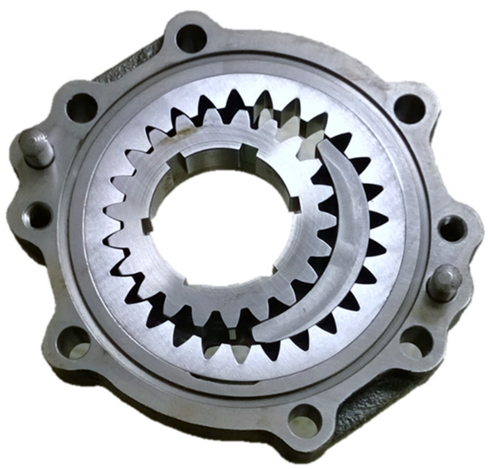

Fig. 8 Photograph of a 150-mm diameter transmission pump assembly.

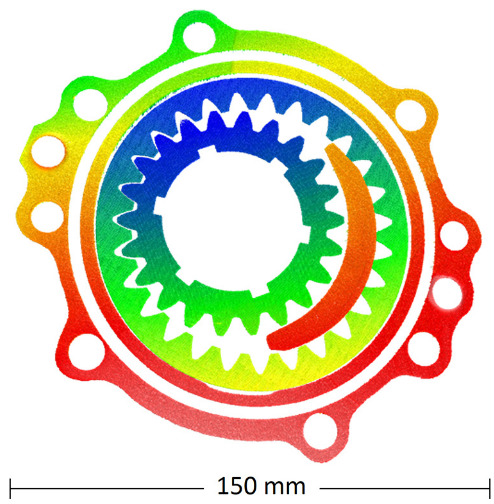

Fig. 9 Measured 3-D image of the part shown in the Fig. 8, using the 0.5× objective. For this image, the height range is $Sz = 119.8$ μm.

The combination of the new objective and field stitching[21] allows for the measurement of areas well beyond the size usually considered accessible to a microscope platform. The benefits of the wide-field objective in this case are significantly reduced data acquisition time and improved form metrology as a consequence of fewer stitched fields. As an example, Fig. 8 shows an assembly of gears in a housing with variable surface textures and discrete surface heights and reflectivities. Figure 9 shows the surface topography of this assembly measured with the 0.5× objective. The measurement is the composite of 29 overlapping CSI image fields acquired and aligned automatically in less than a minute under computer control.

5 Summary

For most of the history of surface topography interference microscopy, the standard objectives have been of the Michelson or Mirau type, with the occasional Linnik for long working distances at high magnifications. The prism-based Michelson objective has traditionally been the choice for low magnifications, but its size and weight limit its use on flexible microscope platforms large fields of view.

We have conceived and developed a class of wide-field objective that is more compact and easier to handle than the Michelson type. A plate beamsplitter replaces the Michelson prism, and the reference path is folded back along the optical axis with a partially transparent reference mirror. The undesired back reflections inherent in this coaxial configuration can be rejected by introducing a small amount of tilt in both the reference and beamsplitter plates. This approach is most effective for NA values limited to <0.1, with higher NA values possible but not without compromise to the imaging quality caused by the asymmetric design.

Specific applications of the design include a 1.4× objective that is parfocal with objectives up to 100×, allowing for rapid changes in magnification without extensive refocusing using a turret. Another application is the measurement of 32-mm square surface areas traditionally considered out of the range of a microscope platform, using a 0.5× objective. The objective type is attractive enough that both the 1.4× and 0.5× are now available as commercial options, referred to as ZYGO wide-field objectives.[20]

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James F. Biegen is a senior technical staff member at Zygo Corporation, specializing in the optical design of advanced metrology instrumentation. His interests range from laser Fizeau interferometry to interference microscopy, covering the complete product development cycle from applied research to manufacturing engineering. His contributions include physical optics modeling and the invention of high-precision interference objectives for both laser and white-light illumination. His work is highlighted in multiple U.S. patents and peer-reviewed journal articles.