CLAIMS

1. A dark-field optical system comprising:

an illumination source;

a rotational objective lens assembly comprising:

a dark-field objective lens configured to collect measurement light from a sample within a collection numerical aperture, wherein the dark-field objective lens includes an entrance aperture and an exit aperture at symmetrically-opposed azimuth angles with respect to an optical axis of the dark-field objective lens;

a rotational bearing to allow rotation of at least a part of the dark-field objective lens including the entrance aperture and the exit aperture around the optical axis; and

a rotational driver to control a rotational angle of the entrance aperture;

a multi-angle illumination sub-system configured to illuminate the sample with an illumination beam through the entrance aperture at any of two or more illumination azimuth angles, wherein a portion of the illumination beam reflected by the sample exits the dark-field objective lens through the exit aperture as a reflected illumination beam, wherein an azimuth angle of the illumination beam on the sample is selectable by rotating the dark-field objective lens to any of the two or more illumination azimuth angles using the rotational objective lens assembly;

a collection sub-system configured to direct at least a portion of the measurement light from the dark-field objective lens to one or more detectors;

a controller communicatively coupled to the one or more detectors, the controller including one or more processors configured to execute program instructions causing the one or more processors to:

receive measurement data from the one or more detectors; and

generate one or more measurements associated with the sample based on the measurement data;

a sample stage for adjusting an angular position of the sample; and

a leveling sensor providing a measurement indicative of an angular position of the sample with respect to the optical axis,

wherein the controller is communicatively coupled to the rotational objective lens assembly, sample stage and leveling sensor;

wherein the controller is configured to direct the rotational objective lens assembly to rotate the dark-field objective lens to the selected azimuth angle; and

wherein the controller is configured to adjust a position of the sample stage during the measurement to provide that the portion of the illumination beam

reflected by the sample exits the exit aperture based on the measurement from the leveling sensor.

2. The dark-field optical system of claim 1, wherein the entrance aperture provides a dark-field illumination path to the sample at a polar angle within the collection numerical aperture.

3. The dark-field optical system of claim 2, wherein the entrance aperture extends through a portion of a housing of the dark-field objective lens and at least one lens element of the dark-field objective lens.

4. The dark-field optical system of claim 1, wherein the entrance aperture provides a dark-field illumination path to the sample at a polar angle outside of the collection numerical aperture.

5. The dark-field optical system of claim 4, wherein the entrance aperture extends through a portion of a housing of the dark-field objective lens and at least one lens element of the dark-field objective lens.

6. The dark-field optical system of claim 1, wherein the measurement light comprises:

at least one of scattered or diffracted light from the sample.

7. The dark-field optical system of claim 1, wherein the multi-angle illumination sub-system comprises:

two or more illumination channels at two or more fixed azimuth angles relative to the optical axis, wherein the rotational driver is configured to selectively rotate the dark-field objective lens to align the entrance aperture to any of the two or more fixed azimuth angles for measurements using the two or more illumination channels.

8. The dark-field optical system of claim 1, wherein the multi-angle illumination sub-system comprises:

one or more rotatable beam-delivery optics aligned with the entrance aperture, wherein the one or more rotatable beam-delivery optics rotate with the dark-field objective lens.

9. The dark-field optical system of claim 8, wherein the one or more rotatable beam-delivery optics comprise:

an optical fiber aligned with the entrance aperture.

10. The dark-field optical system of claim 1, wherein the leveling sensor comprises:

a sample-position sensor to provide a measurement of an angular position of the sample.

11. The dark-field optical system of claim 1, wherein the leveling sensor comprises:

one or more optical detectors positioned to receive the reflected illumination beam.

12. The dark-field optical system of claim 1, wherein the dark-field objective lens includes an additional entrance aperture and an additional exit aperture oriented at symmetric azimuth angles, wherein the multi-angle illumination sub-system is further configured to illuminate the sample through the additional entrance aperture.

13. The dark-field optical system of claim 1, wherein the rotational bearing comprises:

at least one of a ball bearing, an air bearing, or a magnetic bearing.

14. The dark-field optical system of claim 1, wherein the rotational bearing comprises:

a rotatable portion and a fixed portion.

15. The dark-field optical system of claim 14, wherein the dark-field objective lens is secured to the rotatable portion.

16. The dark-field optical system of claim 14, wherein a first portion of a housing of the dark-field objective lens includes the rotatable portion, wherein a second portion of the housing of the dark-field objective lens includes the fixed portion.

17. The dark-field optical system of claim 1, wherein at least one of the entrance aperture or the exit aperture comprises:

a hole.

18. The dark-field optical system of claim 1, wherein at least one of the entrance aperture or the exit aperture comprises:

a notch extending to an end of the dark-field objective lens facing the sample.

19. A dark-field measurement method comprising:

providing an illumination source;

providing a rotational objective lens assembly comprising:

a dark-field objective lens configured to collect measurement light from a sample within a collection numerical aperture, wherein the dark-field objective lens includes an entrance aperture and an exit aperture at symmetrically-opposed azimuth angles with respect to an optical axis of the dark-field objective lens;

a rotational bearing to allow rotation of at least a part of the dark-field objective lens including the entrance aperture and the exit aperture around the optical axis; and

a rotational driver to control a rotational angle of the entrance aperture;

a multi-angle illumination sub-system configured to illuminate the sample with an illumination beam through the entrance aperture at any of two or more illumination azimuth angles, wherein a portion of the illumination beam reflected by the sample exits the dark-field objective lens through the exit aperture as a reflected illumination beam, wherein an azimuth angle of the illumination beam on the sample is selectable by rotating the dark-field objective lens to any of the two or more illumination azimuth angles using the rotational objective lens assembly;

a collection sub-system configured to direct at least a portion of the measurement light from the dark-field objective lens to one or more detectors;

a controller communicatively coupled to the one or more detectors, the controller including one or more processors configured to execute program instructions causing the one or more processors to:

receive measurement data from the one or more detectors; and

generate one or more measurements associated with the sample based on the measurement data;

providing a sample stage for adjusting an angular position of the sample; and

providing a leveling sensor providing a measurement indicative of an angular position of the sample with respect to the optical axis,

wherein the controller is communicatively coupled to the rotational objective lens assembly, sample stage and leveling sensor;

wherein the controller is configured to direct the rotational objective lens assembly to rotate the dark-field objective lens to the selected azimuth angle; and

wherein the controller is configured to adjust a position of the sample stage during the measurement to provide that the portion of the illumination beam reflected by the sample exits the exit aperture based on the measurement from the leveling sensor.

20. The dark-field measurement method of claim 19, wherein the entrance aperture provides a dark-field illumination path to the sample at a polar angle within the collection numerical aperture.

21. The dark-field measurement method of claim 20, wherein the entrance aperture extends through a portion of a housing of the dark-field objective lens and at least one lens element of the dark-field objective lens.

22. The dark-field measurement method of claim 19, wherein the entrance aperture provides a dark-field illumination path to the sample at a polar angle outside of the collection numerical aperture.

23. The dark-field measurement method of claim 22, wherein the entrance aperture extends through a portion of a housing of the dark-field objective lens and at least one lens element of the dark-field objective lens.

24. The dark-field measurement method of claim 19, wherein the measurement light comprises:

at least one of scattered or diffracted light from the sample.

25. The dark-field measurement method of claim 19, wherein the multi-angle illumination sub-system comprises:

two or more illumination channels at two or more fixed azimuth angles relative to the optical axis, wherein the rotational driver is configured to selectively rotate the dark-field objective lens to align the entrance aperture to any of the two or more fixed azimuth angles for measurements using the two or more illumination channels.

26. The dark-field measurement method of claim 19, wherein the multi-angle illumination sub-system comprises:

one or more rotatable beam-delivery optics aligned with the entrance aperture, wherein the one or more rotatable beam-delivery optics rotate with the dark-field objective lens.

27. The dark-field measurement method of claim 26, wherein the one or more rotatable beam-delivery optics comprise:

an optical fiber aligned with the entrance aperture.

28. The dark-field measurement method of claim 19, wherein the leveling sensor comprises:

a sample-position sensor to provide a measurement of an angular position of the sample.

29. The dark-field measurement method of claim 19, wherein the leveling sensor comprises:

one or more optical detectors positioned to receive the reflected illumination beam.

30. The dark-field measurement method of claim 19, wherein the dark-field objective lens includes an additional entrance aperture and an additional exit aperture oriented at symmetric azimuth angles, wherein the multi-angle illumination sub-system is further configured to illuminate the sample through the additional entrance aperture.

31. The dark-field measurement method of claim 19, wherein the rotational bearing comprises:

at least one of a ball bearing, an air bearing, or a magnetic bearing.

32. The dark-field measurement method of claim 19, wherein the rotational bearing comprises:

a rotatable portion and a fixed portion.

33. The dark-field measurement method of claim 32, wherein the dark-field objective lens is secured to the rotatable portion.

34. The dark-field measurement method of claim 32, wherein a first portion of a housing of the dark-field objective lens includes the rotatable portion, wherein a second portion of the housing of the dark-field objective lens includes the fixed portion.

35. The dark-field measurement method of claim 19, wherein at least one of the entrance aperture or the exit aperture comprises:

a hole.

36. The dark-field measurement method of claim 19, wherein at least one of the entrance aperture or the exit aperture comprises:

a notch extending to an end of the dark-field objective lens facing the sample.