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ABSTRACT

Limited light source coherence can be both a complication and a benefit to interferometric optical metrology. Although high-coherence lasers are great for displacement measuring interferometry, holography and Fizeau interferometry, many instruments rely on low coherence as part of the measurement principle. Examples include systems that separate parallel surfaces of transparent parts, coherence scanning interferometers for surface topography, and coupled-cavity fiber position sensors. In cases where high coherence is essential, there can nonetheless be a benefit to synthesizing reduced coherence to suppressing spurious fringes, coherent noise, and unwanted speckle.

Keywords: Interferometry, speckle, coherence, metrology.

INTERFEROMETRY AND COHERENCE

Optical interferometry, fundamentally, relies on the coherent superposition of light waves with nearly synchronized phase fluctuations. For most of the history of interferometric optical metrology, the challenge was to develop useful instruments given the constraints on available light sources. Many clever traditional interferometer designs were driven by the need to accommodate the bandwidth and size of thermal sources and spectral emission lamps [1].

Lasers revolutionized interferometric metrology in the 1960's, enabling stage metrology with displacement interferometry [2] and the now ubiquitous laser Fizeau interferometer for testing of optical components and systems [3]. It is difficult to imagine the instruments pictures in Figure 1 without the availability of reliable, high-coherence lasers.

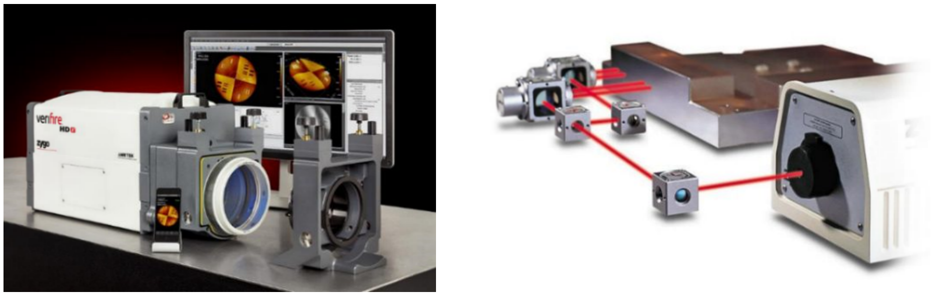

Figure 1: These instruments depend on high-coherence laser sources for their function. Left: Laser Fizeau interferometer. Right: Displacement measuring interferometer.

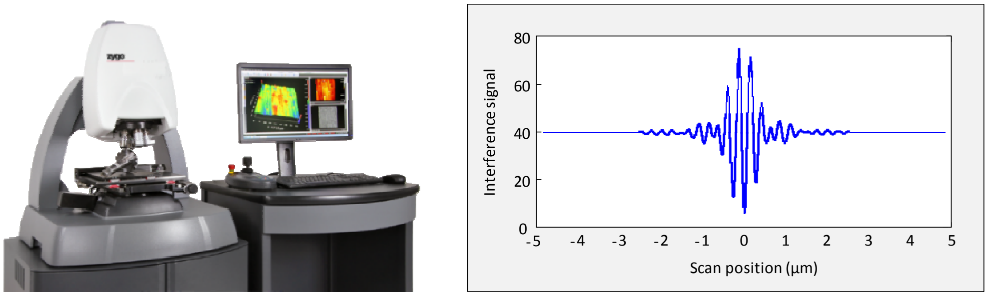

Figure 2: . Left: Modern general-purpose, low-coherence interference microscope for areal surface topography measurement. Right: Interference pattern localized by fringe contrast.

A decade after commercial lasers became available, another enabling technology renewed interest in interferometers that rely on low coherence as part of their operating principle: The desktop computer. The ability to rapidly and automatically digest interference pattern localized by coherence converted the highly-specialized interference microscope into a general purpose areal surface topography instrument. Coherence scanning interferometry systems such as the one shown in Figure 2 use LED sources and acquire and process millions of interference patterns in a few seconds [4].

Other uses for low-coherent light sources include the separation of parallel surfaces of transparent parts [5]. The instrument shown in Figure 3 illustrates a design for obtaining high-contrast fringes from either the front or the back surface of a semi-transparent flat object, using a blue LED source. Similar capabilities are possible with tunable-wavelength lasers, which can scan through multiple wavelengths and emulate the effect of low coherence surface separation [6].

Distributed, coupled-cavity fiber sensors as shown in Figure 4 also rely on broad-bandwidth light sources with low temporal coherence. In this case, a phase delay within the control box is compensated by a matching phase delay in each of several passive sensors [7, 8]. There can be as many as 64 such remote sensors, as well as additional elements such as the small refractometer in the right-hand image of Figure 4. Such sensors are sensitive to minute displacements over short ranges of a millimeter, with a 3σ noise level of 0.01 nm/√Hz.

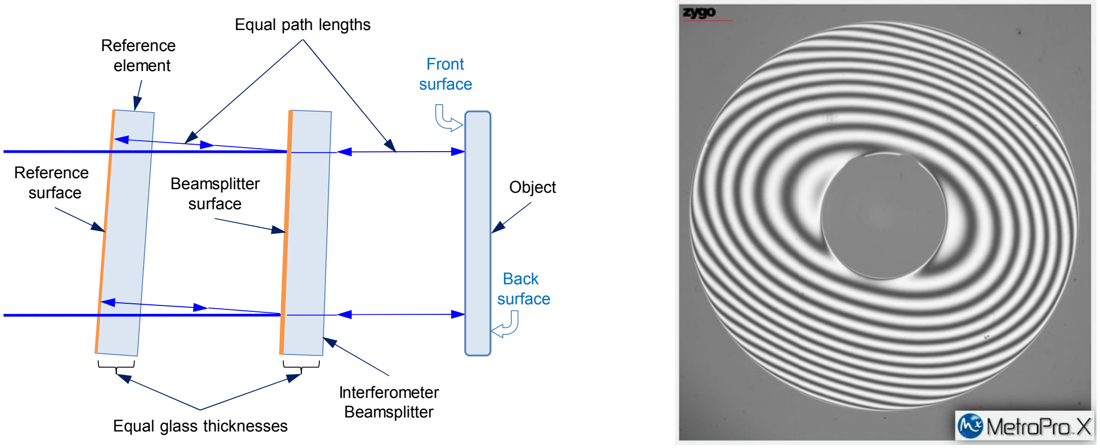

Figure 3: Left: Geometry for equal path interferometry over a large measurement area, for the separation of parallel surface reflections. Right: Interference pattern for the front surface of a 100-mm diameter glass substrate of a data-storage rigid disk drive.

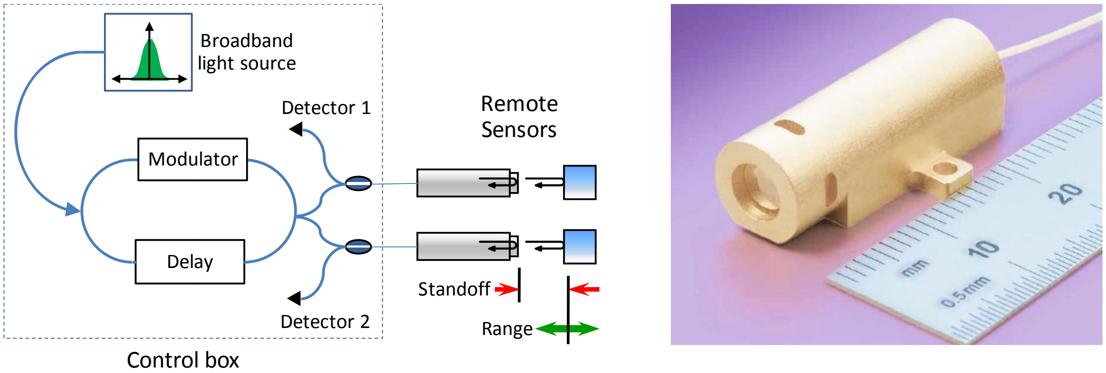

Figure 4: Left: Schematic of a coupled-cavity fiber-optic position sensing system using a low-coherence light source. Right: Refractometer for monitoring the index of air in real time, for use together with the position sensors.

SUPPRESSION OF COHERENT NOISE

Even when a laser is appropriate as a light source, there is often an interest limiting or "busting" the coherence, at least in some portion of the optical system. Coherent noise in interferometric data can take many forms, including speckle noise and the well-known "bulls eye" usually caused by dust on an optical surface. These noise patterns are bothersome in the live images; but more significantly, they can print through to the final surface height maps. Even though the effect may result in only a nanometer or two of surface height variations, the distinctive coherent noise patterns can be at least distracting and at worse a significant source of degradation for the metrology fidelity at high spatial frequencies.

Before the widespread use of lasers, high-coherence sources such as zirconium arc lamps enabled the production of some of the first holograms. It was soon observed that these sources resulted in noisy holograms which in turn led to noisy reconstructions [9]. The solution was to rotate the entire light source unit in a continuous manner about the optical axis of the system [10]. This does not actually remove the sources of noise, but if the time of exposure is long, it reinforces the desired stationary pattern while averaging away much of the coherent noise, which is randomized by the movement of the light source [11-14]. Such averaging may be achieved in many different ways, including rotating the whole optical system, rotating some special optical elements around the axis of the optical system, moving a diffuser across the illuminating beam, changing the incident direction of the illuminating beam with a rotating element. moving different masks in the Fourier plane of the imaging system [15].

The averaging methods developed for holography and coherent imaging have been shown to be effective for improving results in interferometry. Figure 5 illustrates the averaging technique applied to a Fizeau interferometer [16, 17]. In this example, each surface height map is the result of a single camera frame data acquisition using the carrier-fringe method [18, 19]. Between each acquisition, the direction of illumination by the laser light source is changed by eccentric rotation of a lens near the system focus of the Fizeau geometry. The left-hand surface topography image in Figure 5 shows high-spatial frequency structure that is characteristic of coherent noise, and that moves depending on the position of the light source. The average of 16 height maps shown on the right-hand side of Figure 5 is much smoother and is a better representation of the true surface topography, with much reduced coherent noise.

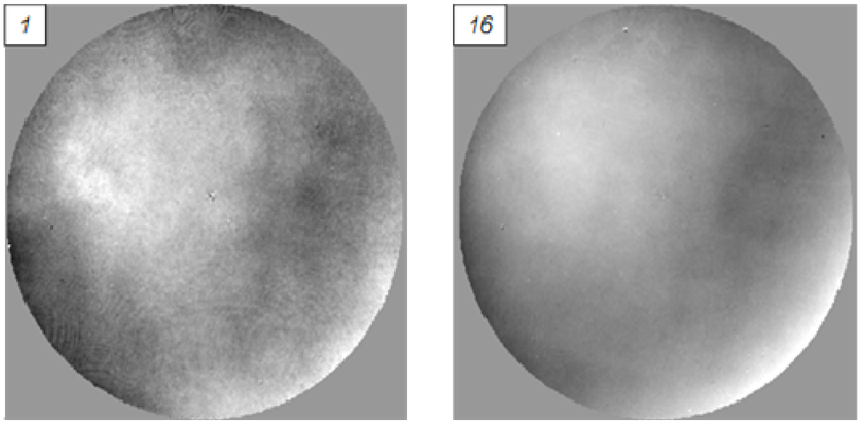

Figure 5: Left: Grey-scale surface height map by reconstruction of an object surface topography from a single camera frame using carrier-fringe methods. Right: Improved image quality after averaging 16 topography maps taken under different illumination conditions.

Another approach to coherent noise reduction is to synthesize a larger monochromatic source size in real time, using a laser in combination with rapidly-rotating mirrors, prismatic elements, or diffusing disks. An advantage of this approach is that the live camera image is improved, and data averaging is not necessary. A basic requirement is that the coherence reduction should not adversely affect the interference fringe contrast, sometimes leading to an adjustable apparent source size [20]. An alternative is to structure the shape of the light source shape so that it does not blur the interference fringes—a strategy underlying ZYGO's "Ring of Fire" method [21].

Sometimes the reduction in coherence follows a fully coherent portion of the interferometer system. Figure 6 illustrates a Fizeau interferometer in which the coherent portion of the instrument generates an interference pattern that is projected onto a rapidly-rotating diffuser. This intensity pattern is then imaged onto the camera [22]. The benefit is that the interference pattern has high contrast, but the optically-incoherent re-imaging portion of the system, which may include multi-element zoom lenses, cannot produce any further coherent noise. Until recently, this basic design with a "coherence buster" was the most popular commercial implementation of the laser-Fizeau geometry. With the advent of large-format cameras, however, the higher lateral resolution of fully-coherent imaging has made it more attractive to directly image onto the camera [23].

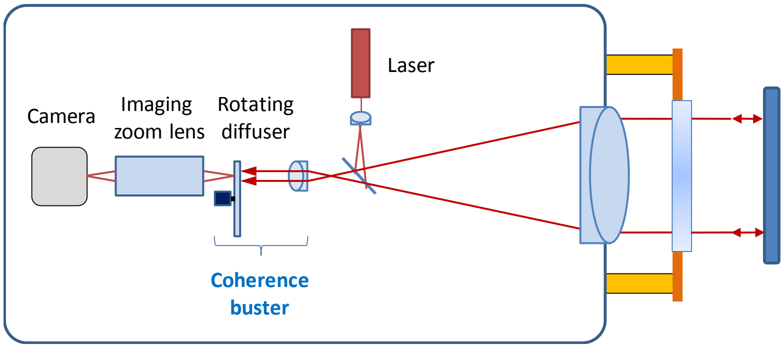

Figure 6: Laser Fizeau interferometer with a rotating diffuser disk to reduce or "bust" the spatial coherence prior to the imaging portion of the optical system.

SUMMARY

Optical coherence is a requirement for interferometry, but as we have seen here, there is a wide range of definitions of what is a useful degree of coherence for a given interferometric metrology system. In some cases, as in Michelson-type displacement measuring interferometers for stage travel over a range of meters, the maximum coherence provided by a laser is essential. In other cases, such as coherence scanning interferometry, it is actually much more desirable to have only a few microns of coherence. Finally, there are many applications where the coherence is a compromise between fringe contrast and coherent noise, and some cleverness is required to balance the two competing requirements. These varying requirements are part of what makes interferometer design a continuously interesting and rich area of technology development.

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