An optical wave is characterized by its amplitude, frequency, phase, polarization, and direction of propagation. When a coherent optical wave is incident on any object, the reflected and/or the transmitted waves contain information about the optical and physical properties of that object. The amplitude contains information about reflectance or attenuation of the object, while the phase gives topography or thickness characteristics. Thus, both these parameters are important for the complete three-dimensional (3D) study of objects. Optical measurement techniques offer significant advantages over their counterparts for imaging and measurement applications. Remote analysis, non-contact measurement, whole field visualization, and no need for special sample preparation are the major advantages. The increasing possibilities of computer-aided data processing have led to a new revival in optical metrology. Recent technological developments and miniaturization of the test objects are creating new challenges for optical metrology, for example, to provide a convenient tool for whole field imaging and micro-systems characterization, and to provide experimental data for computer-aided engineering for fast and accurate measurements, and so on. Different optical methods are used for these measurements depending on the requirements. These methods can be divided into two broad categories, called imaging and interferometric methods, summarized in Figure 1.1.
New challenges for the imaging and measurement processes introduced by the miniaturization of the test objects require the development of reliable advanced testing methods. Some examples are dynamic microscopic imaging (for example, micro-particles image velocimetry, micro-fluids flow analysis, and the study of biological samples), and static and dynamic measurement of micro-structures. The integration of mechanical elements, electronics, sensors and actuators on a common silicon substrate by micromachining technology constitutes a micro-electromechanical systems (MEMS). This has a wide range of applications in scientific and engineering fields. Characterization of the mechanical properties of MEMS structures at different stages of manufacturing is extremely important. The aim of this testing is to provide feedback about device behavior, system parameters, and material properties for the design and

**Figure 1.1 Methods of optical metrology**
simulation processes. Also dynamic testing is needed in the final devices to test their performance and characteristics. 3D imaging and characterization of the mechanical properties of MEMS structures are a challenging task.

Various techniques have been explored to characterize MEMS devices. Thermographic techniques such infra-red radiation analysis, fluorescent micro-thermographic imaging techniques and liquid crystal methods have been used in the thermal characterization of MEMS devices. These techniques, however, have their limitations such as poor resolution, issues concerning repeatability or coating the device with different layer. A non-destructive optical technique for thermal deformation characterization has been used. Though the technique provides a spatial resolution of 0.5–1 μm, the main difficulty arises with the need to know the reflectivity coefficient of the material used. The above-mentioned techniques are useful in estimating the device temperature. To characterize the deformations in the device, different techniques have been adopted, such as a 3D surface profilometer, involving a white light interferometric scanning principle with a stroboscopic LED light source, providing a vertical displacement resolution of 3–5 nm. In-plane motion characterization of MEMS resonators could be performed using a stroboscopic scanning electron microscope imaging technique. The accuracy of the measured displacement using this technique is about 20 nm, limited mainly by the electron probe size and the digital scanning resolution. Laser doppler vibrometry is also one of the widely used MEMS characterization techniques. Frequency response of vibration amplitude of the mechanical structures, along with their vibration modes, can be obtained using a vibrometer, but it cannot provide the static deformation of the mechanical structures. Furthermore, they provide vibration information only at a single point. To analyze the vibrations of a device, the laser beam has to scan the entire structure.

Holography is an important tool for optical metrology. Dennis Gabor invented holography in 1948 as a two-step lens-less imaging process for wavefront reconstruction. The phase, amplitude, polarization, and coherence of a wave field can be stored in a hologram during recording. Since these quantities cannot be measured directly with conventional detectors, which are only sensitive to the intensity, this makes holographic technique most attractive. Holography is well established for scientific and engineering studies and has found a wide range of applications. In classical holography, photographic plates or thermoplastic films are used to record holograms in a vibration-free environment and then are optically reconstructed. The handling of these materials is time-consuming and the vibration isolation requirement makes holographic technique less popular in industrial environments. In addition, when smaller objects are studied, the complicated experimental set-up and evaluation processes during reconstruction often impose challenging problems.

With the development of digital computers and digital recording devices, that is, a charged coupled devices (CCD) and CMOS sensors, digital
holography was proposed to overcome the problems of classical holography. CCD sensors provide the flexibility to record holograms directly in digital form. The reconstruction process is then performed numerically, giving a quantitative analysis of amplitude and phase of the wavefront. This offers new possibilities for a variety of applications, which in classical holography was done only qualitatively. Digital holography is an exciting new method for handling light. The capability of whole field information storage in holography and the use of computer technology for fast data processing open up a lot of possibilities to develop digital holography as a novel metrological tool. This has received increased attention in the past two decades. The main reason for this development has been the rapid improvement in storing and processing of digital information. The object wave can be numerically calculated directly from the holograms and this makes it possible to quantitatively calculate both the amplitude and phase information separately, which is not directly possible in conventional holography and other classical optical metrological methods. These features make it the perfect method for both imaging and measurement. Digital holography has the potential to address recent challenges for optical metrology brought about by miniaturization, new material and processes.

CCD sensors as holographic recording medium allow the recording of holograms at video rates and are in a format readily available for numerical reconstruction. Commercially available CCD sensors have their limitations, such as lower pixel resolution and smaller sensing area. This limited resolution restricts the angle between object and reference beams to a few degrees only. To achieve a good quality reconstruction, the digital recording of holograms has to satisfy the requirements of Nyquist sampling theorem. This implies that interference between two beams of wavelength \( \lambda \) intersecting at an angle \( \theta \) gives fringe spacing \( p = \lambda / \sin \theta \) and it must be larger than two pixels. For example, for 3° interference angle between two beams of He-Ne laser (\( \lambda = 0.6328 \mu m \)), the pixel size of CCD should be 6 \( \mu m \) to fulfill the sampling theorem. This corresponds to the higher end of the CCD cameras. It is interesting to note that it is the pixel size along with number of pixels of a CCD sensor that is also important. An overview of the research work focused on digital holography and its applications explored in the past decade is shown in Figure 1.2.

One of the most remarkable applications of holography is in the interferometric comparison of diffuse wavefronts. This technique uses the vast generalization of interferometry to measure displacement and surface deformation of opaque objects. It involves the double exposure method from two different states of the object. By reconstructing the hologram, the two wavefronts interfere with each other and produce a fringe pattern that describes the changes that have occurred between the two states of the object. The numerical reconstruction process in digital holography makes it possible to numerically measure the intensity and phase for both states of the object directly from the holograms. It is possible to calculate the interference phase directly
from the holograms, which is the phase difference between the two object waves. Also the other methods of optical metrology, for example, shearography and speckle photography, can be numerically obtained from digitally recorded holograms. Ways of measuring micro-deformation based on the principle of digital holographic interferometry have been widely studied.

Digital holography offers new possibilities in the non-invasive measurement of MEMS devices. In digital holography, the numerical separation of amplitude and phase enables the direct determination of the modulo $2\pi$ interferometric phase without the need for any phase shifting method while at the same time the numerical amplitude reconstruction allows for lens-less imaging. Strain analysis has been described by digital holographic methods. By illuminating the object from three directions, all three surface displacement components ($x, y, z$) are calculated during the reconstruction process. These components can be used to find the displacement gradient or strains on the surface. Incorporation of microscopy with digital holographic interferometry improves the capability of measurements for microsystems and has been used to measure deformation with an accuracy of less than 1 nm. Use of digital holographic microscopy (DHM) in MEMS characterization has generated a lot of interest in recent years because of the accurate determination of the deformations due to the residual stress and the impact of thermal loads on deformations. DHM provides a non-contact-based and non-destructive method for static as well as dynamic characterization of MEMS devices. Dynamic digital holography has also attracted great interest in recent years. There are two approaches to this – the first is to use a pulse laser or high speed camera to record multiple frames which are then processed much like the static case. Methods such as pulse or stroboscopic digital holography require
precise synchronization of the light source, specimen and the recording device. The second is to use the time average method which does not require any high speed camera or a pulsed laser. In this book, digital holographic systems that use off-axis geometry and in-line lens-less geometry are presented for micro-size object imaging and measurement (static and dynamic) applications. The in-line digital holographic system has shown better performance due to its higher space-bandwidth product which provides a larger field of view and higher imaging resolution than the off-axis set-up.

This book deals with topics related to micro-measurement with a specific focus on micro-devices and MEMS structures for which digital holography is best suited. In Chapter 2, the reflection mode of digital holography is described, including the recording using in-line, off-axis and lens-less geometries. This is followed by examples of 3D characterization of MEMS devices as well as static and dynamic testing of these components. Specific applications are highlighted in this chapter. Chapter 3 deals with transmission digital holographic configurations. Since in this case the reference and object beams need to be separately formed, some understanding of two beam interference under different conditions is reviewed to highlight the effect of phase compensation. These are then incorporated into the design of three different configurations where the phase is physically rather than numerically compensated. Applications of these are demonstrated for micro-measurements. Chapter 4 deals with the use of an in-line digital holography system for micro-particle sizing and counting both in static as well as in dynamic situations. There is interest in this in the field of crystallization studies, as particles which are both spherical as well as needle-shaped can be measured in a 3D volume. Chapter 5 contains a group of related applications starting with digital tomography (Chapter 5.1), followed by high resolution pulsed digital holography (Chapter 5.2), and finally digital holography for refractive index measurement with applications in photorefractive materials, acoustics, plasmas, turbulent flow and thermal measurements (Chapter 5.3).