Chapter

Introductory Chapter: Interferometry

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1. Introduction

Interferometry has been a very effective tool for science and industry for many years. From optics to astronomy, from materials science to mechanical engineering, interferometry has been instrumental in pushing the boundaries of technological progress. The field has come a long way since one of its earliest mention in the news section of *Nature* in 1920 [1]. At one time optical interferometry relied heavily on on monochromators, limiting the potential applications. Nowadays, the electromagnetic source used in generating fringes is far advanced, owing to the advent of lasers with unprecedented bandwidths and intensities. However, the techniques associated to interference of electromagnetic waves is no longer limited to all optical methods. Incoherent sources can now be made to interfere under certain experimental conditions [2].

The power of interferometry has made it an obvious tool to explore interdisciplinary research in modern times and has expanded to topics related to chemistry, mechanical engineering and material science related topics such as shock spectroscopy, surface profiling, and microfluidics [3–5]. In the recent gravitational wave discovery, it was an interferometer called "LIGO" that made it possible. In this chapter, a brief discussion will be presented on how the field has evolved in different research directions with time along with some examples from the recent literature which has helped the expansion. A brief overview of issues of interferometry technique in general will also be provided where artifacts inherent with the technique will be discussed.

Interferometry represents a set of techniques where, in its most common form, electromagnetic waves superimpose thereby forming interference fringes. The phenomenon involving interference occurs all around us. For example, a drop of oil on water or a soap bubble generates coloration because of naturally occurring interference. In interference, small changes in optical path cause significant and precisely measurable changes in intensity pattern. Using this property, a wide variety of experiments is designed where precise length measurements are necessary. In mechanochemistry, shock science, and detonation studies, measuring free surface velocity is very important. Optical interferometry with the highest time resolution has enabled such measurements. These techniques fall under the umbrella of "laser velocity interferometry" and consist of well-known and established methods such as VISAR, ORVIS, several Quartz-based stress gauges and so on [6]. A similar technique, termed as photon Doppler velocimetry (PDV) has been very useful to probe explosive chemistry in the short length scale with nanosecond time resolution [3]. These interferometric techniques can also accurately investigate shock response in solids. In this technique, typically a single mode laser beam is split into two. One of them is focused onto a moving, flat surface. The surface is usually polished; hence a strong reflection of the beam is generated. The reflected beam combines with the remaining beam, which has gone through a delay line meanwhile, to generate beats. The beats are counted using suitable algorithm to make a velocity history of the surface (i.e., the reflector). The same experiment can be performed in two different geometries, the most common being one where we can record a velocity history for an incoming object. In shocked systems, one can thus obtain information regarding pressure and density evolutions with high time resolution [3, 6]. In another geometry, a thin layer of reflective surface (typically a metal) is deposited at one side of the substrate being shocked, and the substrate is exposed to shock in such a way that the shock emerges through the reflective surface. This is a very powerful technique to generate shock break out profiles and is also used in generating Hugoniot points in materials. A Hugoniot is a collection of data points obtained from single shot shock experiments. Each data point in a Hugoniot curve gives us a shock velocity (U_s) corresponding to a mass particle velocity (U_p). Using this information, one can distinguish between shock loading and unloading mechanisms in solids. In a recent study, the researchers have shown that shock break out experiments in explosives are significantly affected on solid properties if the solids are different in crystallinity [7]. Thus, a highly crystalline sample such as sapphire or calcium fluoride would show different shock break out traces compared to polymer or glassy substances [7]. Gauge experiments are also reputed for accurately generating Hugoniot points. A series of such experiments performed LASL data center is currently being used by the shock community for impedance matching in designing experiments [8].

Interdisciplinary research has seen a great deal of hybrid techniques where two powerful spectroscopic methods are simultaneously used to extract unique information from a system. Fluorescence interferometry (FI) is one such example. There are various configurations of FI. In one variant, the self-reference interferometer consists of lenses that gather light from two sides of the sample simultaneously after the main beam is split using suitable optics [9]. The two beams are used as excitation and probe [9]. In another version, a Fourier transformed signal is used to generate a time domain information [9]. In general, fluorescence interferometry is very powerful as it complements the traditional fluorescence experiments by extracting the phase information. Such experiments have already provided with high resolution single shot images in biological specimens with marking capability [9]. Several ongoing and future research efforts are focused on getting a reliable, detailed 3D image using selective markers with the help of quantum dots. In summary, more advanced techniques such as optical nanoscopy is where FI is going to be very useful.

Another established area of research that benefitted greatly is materials science laboratories where optical materials are characterized using either white-light-interferometry or where interferometry is used for surface profiling [10, 11]. Both two- and three-dimensional optical profilers use interferometry to accurately map surface roughness. In the most common set up, an optical profiler uses the optical path difference to generate interference fringes between two signals coming from a reference surface and a "signal" surface. The "signal" surface is basically the surface under investigation. Many commercial optical profilers (for example, Zygo) are in operation in modern characterization laboratories [11]. Surface profiling is very crucial for understanding stress models in solids. There is a huge demand of modeling solids under stress. A lot of efforts are being made currently in those directions, where one would be able to numerically simulate response of solids [12]. To do that, the model should be robust enough to successfully simulate existing experimental data. There are open questions related to chemical kinetics and initiation of energetic materials which could be answered once the models can accurately simulate current high-resolution interferometry data [13]. One such example is the reactive and flow model "ALE3D," developed at Lawrence Livermore National Laboratory [14].

In fields such as industrial sensing and space engineering, measuring distances with high precision is important, where a traditional form of single-wavelength interferometry has been used in the past [15]. To get the distance, a fringe counting algorithm is used in single-wavelength interferometry, which sometimes can cause errors in position measurements [16]. However, a relatively new technique called multiple-wavelength interferometry has been in practice recently which avoids fringe counting [17]. The technique has lots of advantage such as capability of measuring very small distances, flexibility, etc., with one small disadvantage; it requires several synthetic wavelengths for increasing the experiment range of the system, thereby increasing complexity of the technique. To solve this problem, researchers have started to use a frequency comb, which emits equally spaced ultra-short pulses [17]. These pulses are spread over a broad spectrum with discrete and uniform modes. The modes are also spaced equally, with very narrow lines [17]. This resembles an ultra-accurate ruler, with deviation in the order of 70 nm for a measurement of 100 mm length [19]. Frequency combs are generated in different ways such as 4-wave mixing or using a mode locked laser, or even by electro-optic modulation. In 2005, Theodor W. Hänsch and John L. Hall shared half of the Nobel prize in Physics for the discovery of a group of precision spectroscopy techniques, including optical frequency comb [20].

There are several applications of precision interferometric methods in metrology, materials science, satellite technology, and a myriad of similar fields where optoelectronic and photonic properties are utilized. As mentioned earlier while briefly discussing white light interferometry (WLI), a series of novel quantum optical techniques employed for reducing noise in a superposition signal, to avoid third-order dispersion, and thrive on interferometric equalization [21]. The resulting variant of WLI is called quantum-WLI (or Q-WLI). Q-WLI is a fast, all-optical technique for investigating material properties with high precision [10].

Despite its versatility and impact, there are some areas where optical interferometric effects make spectroscopy very difficult to perform. One such example is a coherent artifact occurs in ultrafast degenerate pump-probe experiment with femtosecond pulses, where the strong signal at temporal overlap of the two beams screens the actual rise time of the “true signal” [21]. A degenerate pump-probe experiment (DPP) is the case where both the pump and probe are of same wavelengths [22]. DPPs are heavily used in probing novel materials to extract signatures of many-body effects in electron/spin scattering mechanisms [21, 22]. By varying the relative intensities of two beams, or by adjusting the polarization angle that effect can be corrected [23, 24]. Interference patterns generated by unwanted resonance can thus affect optical measurements. There are various experimental scenarios of light-matter interaction where signal to noise ratio needs to be very high. Raman scattering measurements, photoluminescence and fluorescence experiments, quantum confinement studies, spin injection and manipulation studies, absorption spectroscopy, and many such complex and delicate probing techniques rely on efficient collection of photons. It is important to understand the limitations in those collection processes as the measurement is designed, since interference of signals can obscure the data one is looking for. For example, while measuring transmission spectra from a thin film, or a layered material, interference effects are observed as oscillations in the spectra [25]. Sometimes, the effect is welcome when the film thickness is unknown and needs to be measured [26, 27]. At other times the interference effect makes it difficult to efficiently fit the spectra to get important band parameters in solids [28]. In photoluminescence measurements, such effects can change the linewidth and the analysis based on broadening of the signal gets affected [29, 30]. In micro and nano-fabrication techniques, and various laser based thin-film deposition systems, interference effects are also visible [30]. A recent paper attempted to analyze intrinsic photoluminescence stoke shift in pulsed laser deposited thin film of CdS to interpret physical meaning of a phenomenological parameter used in Urbach model [30]. The same paper also tried to look at the Raman peaks and probed the phonon population by calculating Huang-Rhys factor [30]. Raman lines are particularly susceptible of background noise, and there are many techniques developed for enhancing Raman signal. A recent study concluded that interference effects are crucial in the micro-Raman spectroscopy of graphene and must be included in analysis when extracting various material information from the spectra [31]. As we move into ternary and quaternary alloys and magnetically doped novel materials for ambient operable devices that successfully exploit charge and spin mobility, experimenters have come to avoid any such effects in the measurement scheme [32].

On February 11, 2016, observation of gravitational waves was announced from the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) [33]. It has become one of the most significant scientific landmarks of recent times, prompting a Nobel prize in 2017 to Rainer Weiss, Kip Thorne and Barry Barish for their contribution towards this discovery [34, 35]. A detailed description of LIGO is out of the scope of this chapter. In short, the apparatus is a Michelson interferometer built at a massive scale [35]. Just like the Michelson-Morley experiment made a conclusive discovery in 1887 to disprove "Luminiferous Aether," LIGO-interferometer measurements have conclusively detected presence of a gravitation waves. It is clear from the updates presented above, how interferometry is one of the most advanced and precision techniques presently being pursued. The development in the field of laser technology has made the progress rapid. Very high time resolutions are being increasingly attained using attosecond laser pulses [36]. This is another huge improvement in understanding reaction mechanisms and will enable scientists to understand processes involved in solar cells by watching in real time the detailed step-by-step energy flow/conversion [36].

To summarize, interferometry is undoubtedly one of the most thriving and rapidly progressing experimental techniques. With applications in so many different fields, interferometers are going to be employed with increasing fashion. The versatility makes the technique almost indispensable in high precision spectroscopy and novel materials. The small and large-scale applicability made it an automatic choice as a consistent and transferable tool. The fact that two of the historic discoveries were made in the field of Physics on interferometer vouches for its power and significance. With increasing finesse in laser engineering, ultra-short laser-pulse based interferometers are going to resolve fundamental mechanisms of physical and life sciences with even greater detail, and this will impact a few of the most urgent technological needs modern society face today: renewable energy/energy harvesting, incorporating devices in biomaterials, and scarcity of resources.

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