Assembling Interferometers and *In-Situ* Observation of Ambient Environments and Solid-Liquid Interfaces

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Abstract

The principle of interferometers and its applicability to our research on crystal growth can be understood through assembling interferometers. In particular, practical skills such as techniques for assembling interferometers and selecting optical components, which are not covered by general textbooks, can be learned.

Keywords: Interferometry, Crystal growth, Concentration field

1. Introduction

Light (electromagnetic waves) has been used to measure physical quantities in various fields for many years. Examples include velocity measurement using Doppler shift, time measurement relative to the speed of light, and distance measurement using a reflected wave, which can be performed relatively accurately and easily. In particular, interferometry is a very powerful tool because small differences in the phases of two or more light paths created by the division of the initial beam enables us to analyze small differences or changes of optical path length.

Interferometry utilizes the properties of electromagnetic waves, namely that when two or more light rays with the same wavefront are superimposed, the intensity of light rays with equivalent phase, i.e., the difference in optical path length is an

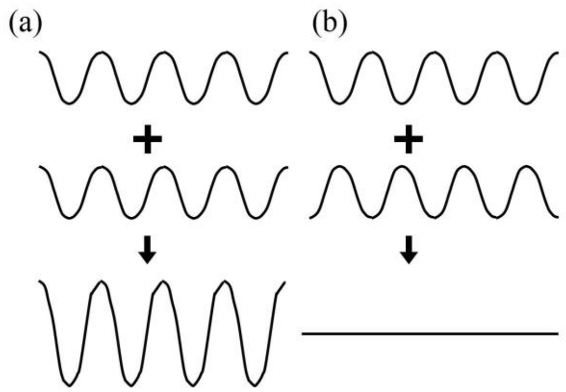

Fig. 1. Schematic of principle of superposition for (a) waves with equivalent phase and (b) waves with a difference of half a wavelength.

integer multiple of the wavelength, is increased (Fig. 1a), while the intensity of light rays with a difference of half a wavelength is reduced to zero (Fig. 1b). The two light rays must come from a single light source, otherwise the light rays will not cause interference. Interference fringes deviate as a result of a difference in optical path length generated by a change in the refractive index of the sample. A laser light, which has high coherence, is useful for making interference fringes. Optical path length is defined as the product of refractive index *n* and distance *l*. If we consider the analogy of walking on a moving walkway in the reverse direction, the speed of the travelator corresponds to the refractive index. Likewise, the optical path length is regarded as the distance that light feels when light travels. Therefore, the optical path length becomes larger in proportion to the refractive index. Since the growth of a crystal is sensitively affected by its surrounding environment, the observation and measurement by a non-contact method using light is particularly effective for studying of crystal growth and therefore it has been used for many years and is still evolving [1-2]. Here, we consider the principles and characteristics of two basic interferometers, Mach-Zehnder and Michelson, and the analytical methods required to apply interferometers in research work.

2. Interferometry

Electromagnetic waves can interfere with other electromagnetic waves that have the same frequency and a constant difference of phase in measurement time and space. In an interferometer, light from a single source is divided into several light rays (usually two) of the same intensity by amplitude, wavefront or polarization division using a half mirror. When the frequency or phase difference is random, interference fringes disappear and an image with

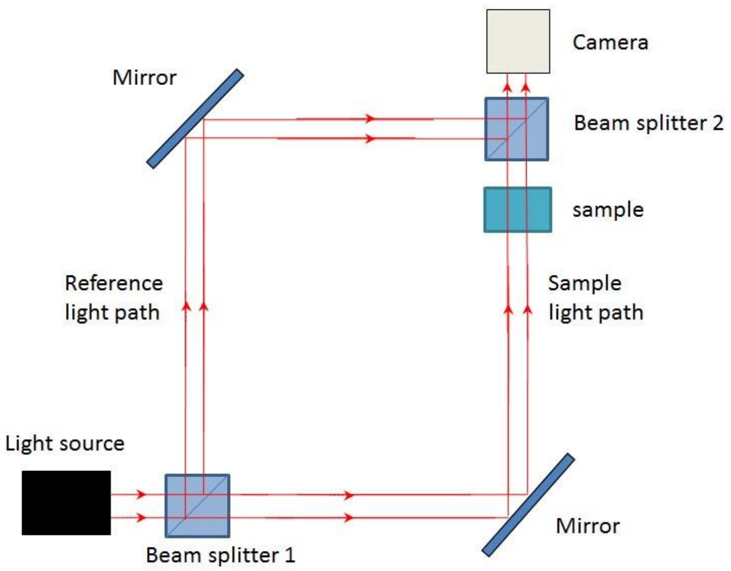

Fig. 2. Schematic of Mach-Zehnder interferometer.

uniform intensity is formed due to time averaging. Famous experiments using an interferometer are Young's interference experiment in 1803 and a double-slit experiment using electrons, which clearly demonstrated the dual character of waves and particles of light and matter [3].

3. Mach−Zehnder interferometer

The Mach−Zehnder interferometer was independently proposed by L. Mach and L. Zehnder in the 1890s. Schematic illustration has been shown in Fig. 2. Collimated light is divided into two light rays at beam splitter 1. One becomes the reference light, which is reflected light on the left side in Fig. 2, while the other passes through a sample and so the wavefront changes. When the two light rays combine at beam splitter 2, the wavefronts of the two light rays have some difference; interferometry measures the value of this difference. Figure 3 shows an example of interference fringes using a collimated He-Ne laser with a wavelength of 632.8 nm. When two light rays, a reference and a sample have no difference in wavefront, the image has homogeneous brightness as shown in Fig. 3a [4]. If either one of the mirrors is tilted to create a difference in optical path length between the upper and lower parts of the image, horizontal stripes appear as shown in Fig. 3b. Tilting the mirror further increases the difference in the optical path length, causing more dense horizontal stripes (Fig. 3c). A pair of blight and dark fringes shows the difference in optical path length at 632.8 nm. When a sample is placed in the optical path, the difference in refractive index between the atmosphere and the sample causes a difference in optical path length. As a result, the interference fringes change. When observing of the sample environment such as temperature and concentration, a compensator (e.g., a glass plate) having a similar refractive index with the sample should be

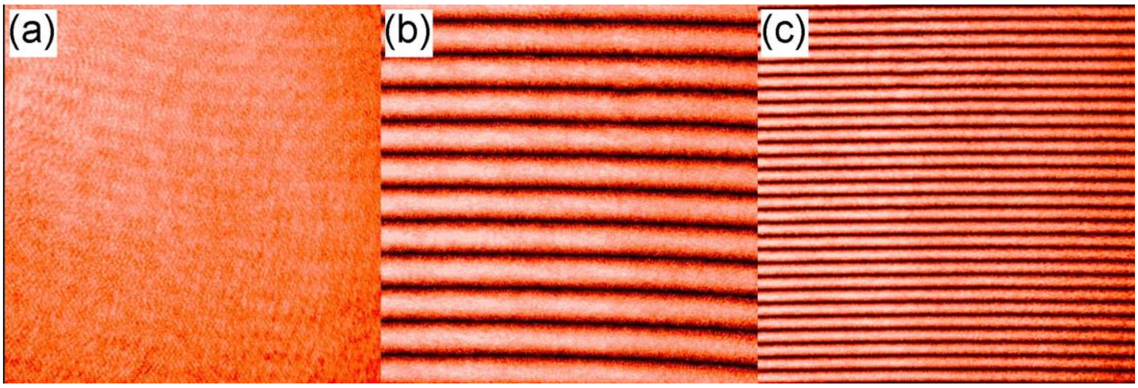

Fig. 3. Example interference fringes by a Mach−Zehnder interferometer. (a) This is an infinite fringe. Homogeneous brightness is a result of similar optical path length between reference and sample light rays. (b) This is a straight parallel fringe (finite fringe). The image has a gradient of optical path length from above to below caused by tilting of the mirror. (c) Larger gradient causes denser fringes.

introduced into the reference light path. The interferometer allows us to measure the concentration or temperature profile around a sample without contact [5-8].

4. Michelson interferometer

The Michelson interferometer was proposed by Albert Abraham Michelson in the early 1880s. The principle of this interferometer is the same as that of the Mach-Zehnder interferometer, with the main difference being the configuration of optical path. In the Michelson interferometer, both the sample and reference light rays pass through the route two times due to the reflection of light rays on the sample surface and the mirror, respectively. The sample and reference mirror are placed at the same distance from the beam splitter as shown in Fig. 4. In general, the reference mirror is called the reference plane. If a thin film is formed on the sample plane or a crystal sitting on the sample plane is grown, interference fringes deviate due to shortening of the optical path length. If a spiral or two-dimensional growth island is distributed on a crystal surface, the difference in height causes deviation of the interference fringes [9-12]. As a result, the surface profile can be measured without contact.

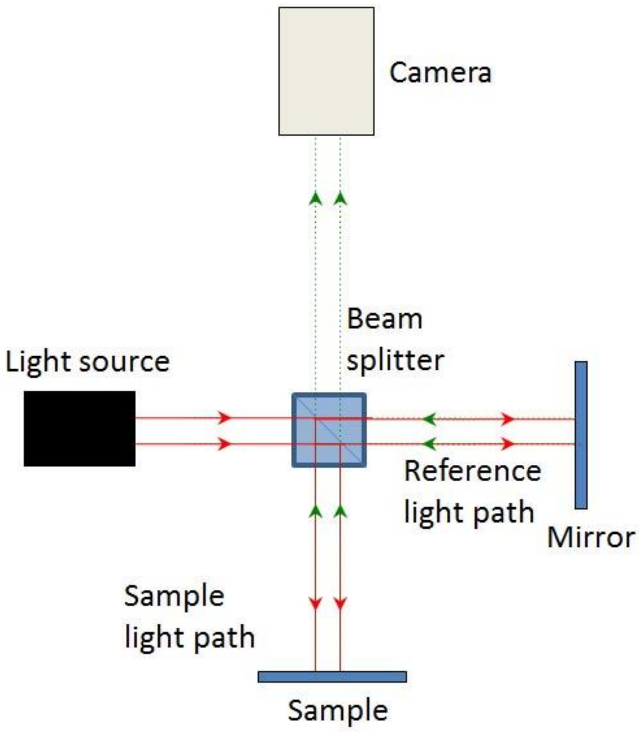

Fig. 4. Schematic of Michelson interferometer.

5. Analytical methods of interference fringes

Interference fringes can be considered like contours on a map. A train of fringes is the result of the same difference in optical path length as that of the reference light. The distance between fringes is determined by the gradient of the optical path length and the wavelength of the light source. The fringes deviate due to state variations of the sample. Thus, the deviation of a fringe, Δd, depends on the variation of refractive index, Δn (= $n_\mathrm{i} - n$), the distance of refractive index changing, l, and wavelength, λ, and follows Eq. (1). In the case of a Mach−Zehnder interferometer, interference fringes deviate due to the variation of refractive index from n_i to n over distance l. When observing a growing surface by a Michelson interferometer, interference fringes deviate due to the shortening of optical path length Δl due to the growth of crystal in r and the following Eq. (2). Thus, the variation of the optical path length Δl corresponds to $2r$, because the light is reflected on the crystal surface paths in the same optical path.

$$\Delta d = \Delta n \frac{l}{\lambda} \quad (1)$$

$$\Delta d = n_i \frac{2r}{\lambda} \quad (2)$$

For example, in the case of an interferometer with a laser light source of wavelength 632.8 nm, the deviation of one line corresponds to a variation of optical path length, nl, of 6.328×10^{-7} m. This Mach−Zehnder interferometer is able to detect minute differences in refractive index as small as $10^{-4} - 10^{-5}$, assuming the size of the sample is 1×10^{-3} m (1 mm). In the case of a Michelson interferometer, fringes deviate in one line for growth of 2.11×10^{-7} m, when the refractive index of the solution is 1.5. For instance, the growth rate of a crystal growing at the rate of 1 nm/s can be determined to within 1 min.

6. Tasks

Divided into small groups, try to make a Mach−Zehnder or Michelson interferometer by arranging the optics yourself. Then, place an ice pillar at the position of the sample, which decreases the temperature around the sample and causes a temperature gradient from the ice surface to the atmosphere when using the Mach−Zehnder interferometer. You will find that the physical length, l, affects the deviation of interference fringes by using ice pillars of different sizes. Using the Michelson interferometer, interference fringes on the crystal surface of a sodium chlorate crystal in solution will be observed. The growth and/or dissolution rates of the crystals can be determined using a temperature control stage. In addition, the equilibrium temperature can be determined based on the interference fringes at the interface between the sodium chlorate crystal and solution.

References

[1] A. A. Chernov, L. N. Rashkovich, A. A. Mkrtchan, *Journal of Crystal Growth* **74** (1986) 101-112.

[2] K. Murayama, K. Tsukamoto, A. Srivastava, H. Miura, E. Yokoyama, Y. Kimura, *Cryst. Res. Technol.* **49** (2014) 315-322.

[3] A. Tonomura, J. Endo. T. Matsuda, T. Kawasaki, H. Ezawa, *Amer. J. Phys.* **57** (1989) 117-120.

[4] Y. Kimura, H. Miura, K. Tsukamoto, C. Li, T. Maki, *Journal of Crystal Growth* **316** (2011) 196-200.

[5] A. Srivastava, K. Tsukamoto, E. Yokoyama, K. Murayama, M. Fukuyama, *Journal of Crystal Growth* **312** (2010) 2254-2262.

[6] Y. Kimura, K. Tsukamoto, *J. Jpn. Soc. Microgravity Appl.* **28** (2011) S9-S12.

[7] Y. Kimura, K. K. Tanaka, H. Miura, K. Tsukamoto, *Crystal Growth & Design* **12** (2012) 3278-3284.

[8] Y. Inatomi, M. Ashida, K. Sakata, T. Okutani, *World Journal of Engineering* **11** (2014) 41-48.

[9] P. G. Vekilov, M. Ataka, T. Katsura, *Journal of Crystal Growth* **130** (1993) 317-320.

[10] A. E. S. Van Driessche, F. Otálora, G. Sazaki, M. Sleutel, K. Tsukamoto, J. A. Gavira, *Crystal Growth & Design* **8** (2008) 4316-4323.

[11] A. E. S. Van Driessche, J. M. García-Ruíz, K. Tsukamoto, L. D. Patiño-Lopez, H. Satoh, *Proceedings of the National Academy of Sciences* **108** (2011) 15721-15726.

[12] I. Yoshizaki, K. Tsukamoto, T. Yamazaki, K. Murayama, K. Oshi, S. Fukuyama et al., *Review of Scientific Instruments* **84** (2013) 103707.