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Review

Overview of the laser-wavelength measurement methods

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ABSTRACT

An overview of existing methods of wavelength and wavelength instability measurement is presented. The methods are classified on the basis of the applied physical phenomena. Three main groups are distinguished: interference comparators, optical beating methods, and methods using specific wavelength-dependent material properties. The main metrological and usage parameters of each group are summarized. Finally the main areas of application of each group are indicated.

1. Introduction

Knowledge of the wavelength of the laser is basic information in most applications of this light source. The first review of laser wavelength measurements was presented in 1977 by Solomakha and Toropov [1]. Since then, the field has grown tremendously. A huge number of methods and techniques for measuring light wavelengths are available and a complete review would require a monograph several dozen pages long. We would like to present herein only a quick overview of the current state of knowledge in this domain. References cited are arbitrarily selected so as to provide representative examples of ideas and devices.

In general, the laser wavelength and wavelength instability measurement methods can be classified into many categories that often overlap. Among the many possible criteria for the classification of these methods for their further presentation, we have chosen division according to the physical phenomena used.

The following three general groups of methods can be distinguished: interference comparators, optical beating methods, and methods using specific wavelength-sensitive material properties (see Fig. 1). The first group of interference methods is based on the analysis of the phase of interference fringes obtained for a reference and tested laser when an optical path difference is introduced in the interferometer. The second group of interference methods comprises techniques based on the analysis of the period of interference fringes in, for example, a Fabry–Perot or Fizeau interference configuration. Comparison of the reference and the test wavelengths is done by determining the ratio of fringe periods of the two lasers. In these methods, it is also possible to measure the wavelength of the laser without the use of a reference. The last group of interference methods comprises spectrum analyzers based on Fourier transform interferometers.

Methods using optical beating do not require an interferometer, that is, an optical system in which an optical path difference exists. The idea of these methods is based on measuring the frequency difference between the reference and tested lasers observed by a high frequency photodetector.

The last group comprises methods that utilize specific wavelength-dependent material properties. The following three main techniques can be distinguished within this group: methods based on optical fibers' feasibilities, techniques based on a change in the polarization of the light, and methods based on the special wavelength-sensitive structure of photodetectors.

2. Interference methods

2.1. Methods based on analysis of the phase of interference fringes

Among the wavelength measuring methods that evaluate the phase of fringes generated in an interferometer, the most common are measurement systems that use the Michelson-type interferometer with mirrors [1] or cube corners [2–5]. The Kowalski interferometer [6] and the Mach–Zehnder interferometer [7] are also used. The idea of the method is based on introducing beams of the tested and reference lasers simultaneously into the interferometer and observing separately the phases of the fringes generated by both applied wavelengths. By changing the optical path difference in the interferometer, a change of the observed fringe phases is obtained, which is directly proportion to the compared wavelength. The reference wavelength and change in observed fringe phases are the basis for the calculation of the tested wavelength.

The base system of this type is shown in Fig. 2. The beams of the reference laser, RL, and the tested laser, TL, are introduced into the interferometer using the polarizing beam splitter cube PBS1. The polarities of the beams of the compared lasers are perpendicular to one another.

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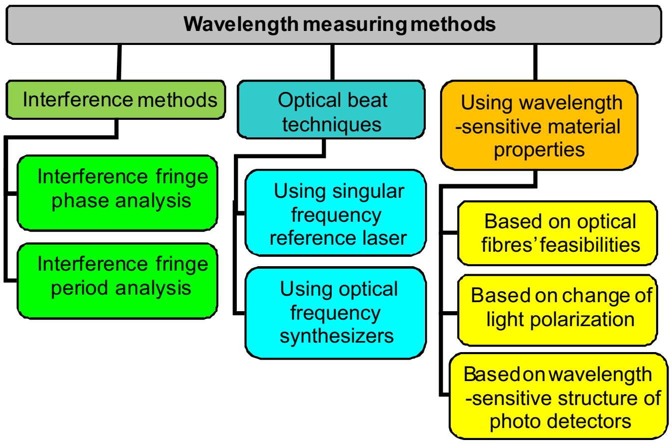

Fig. 1. The proposed classification of the methods of measuring laser wavelength.

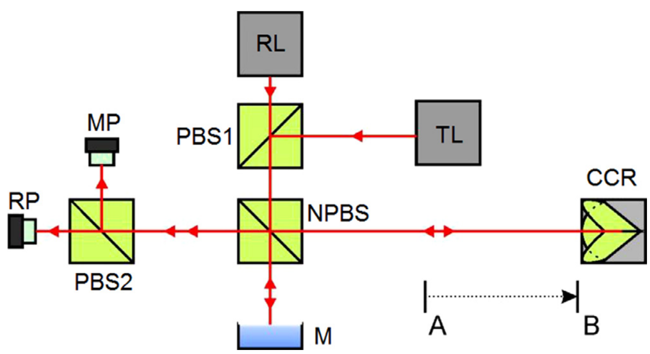

Fig. 2. Michelson-type interferometer with a moving corner cube for comparison of the wavelengths of lasers.

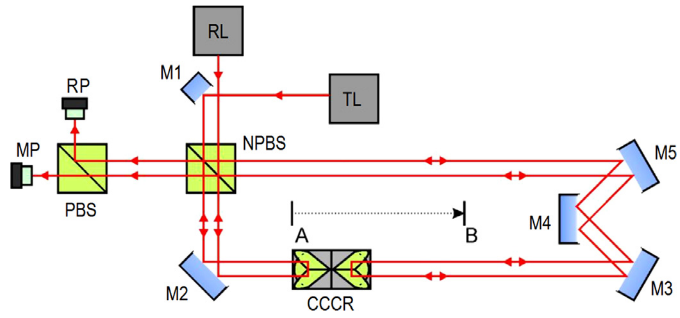

Fig. 3. Michelson interferometer with double movable cube corners.

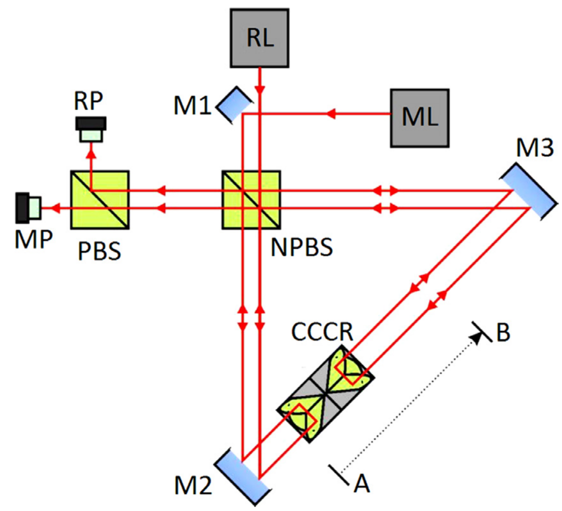

Fig. 4. Michelson interferometer with a moving pair of cube corners and two light-directing mirrors.

The main interferometer is formed by a non-polarizing beam-splitter, NPBS, a plane mirror, M, in one arm, and a cube corner reflector, CCR, in the second arm. The cube corner reflector is applied in order to make the system insensitive to the angular tilts of the moving reflector.

A second polarizing beam-splitter cube, PBS2, separates the interfering beams of the compared lasers and directs them into reference and measured signal photodetectors, RP and MP, respectively. This configuration requires precise coaxial coverage of the beams. In this system there are problems with the quality of the interference fringes, due to diffraction effects caused by CCR edges.

In order to eliminate this difficulty, the mirror has been replaced by identical corner cubes [2,3] wherein the beams of both lasers still have to be coaxial. Such a system has been modified by applying the parallel beam interferometer [4–6]. Laser beams are introduced into the interferometer in parallel (not coaxially), which reduces power loss and does not change the beam polarization. The system does not require a polarizing beam-splitter at the input of the interferometer to connect beams and an identical element at the output to divide them. The system shown in Fig. 3 has the abovementioned solution. By using the combined cube corner reflectors, CCCRs, the change in the optical path difference is doubled, which reduces the dimensions of the interferometer [7,8]. This method allows successive doubling of changes in optical path difference by changing the setting of the mirrors and combined cube corner reflectors CCCRs, relative to each other [9,10]. In this setup, the polarizing beam-splitter, PBS, has been applied only for a more convenient arrangement of the photodetectors, RP and MP.

In the systems presented above, the mechanical stability of the applied mirrors causes many problems. In order to avoid them, the proposition represented in Fig. 4 has been applied [11,12]. This system makes the adjustment and maintenance of mechanical stability much easier. Numerous modifications of this system have been applied, referring mainly to the method of introducing the two laser beams into the interferometer. A coaxial input beam was used as shown in Fig. 2 [13,14]. A fiber optic system was applied [15] in order to eliminate the cosine error caused by the angle between compared beams.

The above structures of Michelson interferometers are the most common, but besides them, there are many systems that combine features of individual solutions. An interesting example of such a solution is the measurement assemblies consisting of two interferometers in which each laser beam moves in an independent optical system. Separation of optical systems makes it possible to eliminate the problems of mixing and separation of the beams. Both interferometers are arranged so that one of the arms of each interferometer overlaps with one axis. A two-sided mirror [16] or double-cube corner reflector [17,18] can be placed along this axis. By using additional cube corners [19,20], the need to steer the mirrors has been removed. A similar effect was achieved by replacing the beam-splitting cube by Fresnel triple dice [21].

Among the methods that use analysis of the phase of interference fringes, the Kowalski interferometer deserves special attention due to the simplicity of its construction [22,23]. The idea of it is presented in Fig. 5.

Reference, RL, and measured laser, ML, beams are placed coaxially and run in opposite directions, entering non-polarizing beam-splitting plates, NPBSP1 and NPBSP2. These plates divide each beam into two: one part entering the photodetector P1/P2 directly and the second being firstly transmitted by the joint corner cube reflector, CCR, before entering the photodetector. The displacement of the CCR changes the optical path difference in the interferometer differently for the two wavelengths. An important advantage of this solution is the very compact design and relatively small number of optical elements, which improves the stability of the setup.