Interferometric Sensors.

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Abstract — over a long period of time optical interferometry was being associated with precision measurements. And an interferometer is an instrument that allows make very precise measurements of objects by using the interference pattern as the result of falling at least two beams of light on the same place. Moreover, if these beams of light are mutually coherent, then the resultant intensity periodically varies depending on the optical path difference and the period (wavelength). In the such way optical path lengths can be estimated on the scale of the wavelength of light. Also it became known that optical fibers guidance properties have dependence on the environment (pressure, temperature, strain, etc.). So any variation of the temperature or strain is measurable. By using single mode fibers and their components makes it possible to build very robust interferometers to be used in laboratories and beyond them. Nowadays fiber optic interferometers are the part of a wide range of new kinds measuring tools.

This article is concerned with the sensors whose historical principles taken into account.

Keywords: *fiber optics, interferometric sensors, optical fibers, optical-fiber sensors, interferometry, optical processing.*

I. Introduction

Interferometric sensor is an instrument based on the interference of waves [1]. There are IS for sound waves and electromagnetic waves (optical and radio waves).

An acoustic IS is an instrument for measuring the physical characteristics of sound waves in gases or liquids. It may be used to measure velocity, wavelength, absorption, or impedance [2-3]. It can also be used for measuring the acoustic attenuation coefficient of the medium, but the accuracy is not high [10]. A vibrating crystal creates the ultrasonic waves that are radiated into the medium. The waves strike a reflector placed parallel to the crystal. The waves are then reflected back to the source and measured.

Optical IS are used for measuring optical wavelength of spectral lines, refractive index of transparent media [4], absolute and relative measurements of length [5-7], angular diameter of objects in the sky [8], testing the quality of surfaces in the optical industry [9].

II. Interferometers

The principles behind all types of IS are very similar. However there is just difference in coherent waves getting and in measurable value. A single beam of light will be split into two or more coherent beams by some kind of splitter device. Each of these beams travels a different optical route and are recombined before arriving a detector. Finally the result of interference between them are shown on a screen. The characteristics of the interference pattern depend on many parameters: the method of the beam splitting into coherent beams, amount of interfering beams, the difference in optical distance, light intensity, the nature of the light source, the spectrum of the light.

Techniques of a coherent waves producing in IS are very various therefore many IS constructions are exist. Optical IS can be divided into two-wave interferometers and multi-beam interferometers by the number of interfering beams. Multi-beam IS are used as an interference spectrum analyzer for spectral composition of light. **Two-wave IS** are used as an interference spectrum analyzer and a device for physical measurements.

MICHELSON INTERFEROMETER is an example for the two-wave IS (Figure 1. from [1]).

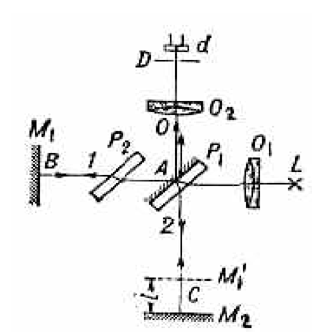

Figure 1. Diagram of a Michelson interferometer: P2 is a plate that compensates for the additional path difference that arises because ray 1 passes through plate P1, twice

A Michelson interferometer consists of two highly polished mirrors *M1* and *M2*. A source L emits light that goes through lens *O1* and hits semitransparent plate *P1* that splits beam into two coherent waves *1* and *2*. *P1* is partially reflective, so one beam is transmitted through to point B while the other is reflected in the direction of *C*. These beams are reflected by the mirrors *M1* and *M2*. Then they go back in direction *A* but beam *2* goes through semitransparent plate *P1* and beam *1* are reflected by it and after transmission of the semitransparent plate they join again. Both beams goes through lens *O2* and produce an interference pattern visible to the observer at point *D*.

Observed interference pattern is equal to interference in air produced by mirror *M2* and virtual pattern *M'1* of mirror *M2* on semitransparent plate *P1*.

The difference in optical distance is equal to *D=2(AC-AC)=2l*, where *l* — distance between *M2* and *M'1*. If the mirror *M1* is set in such way that M'1 is parallel to *M2*, then stripes of equal slope are appeared in the focal plane of the lens *O2*. If *M2* and *M'1* form optical wedge then stripes of equal depth are appeared in the plane *M2M'1*.

The Michelson interferometer is used in physical measurements and engineering instruments. Using it for the first time absolute value of light wavelength was measured. And the speed light independence of the orientation of the apparatus are proved (Michelson–Morley experiment, [11]).

Michelson spectrographs are capable of very high spectral resolution observations of very bright sources (Fourier transform spectroscopy, [12]). This is just a Michelson interferometer with a movable mirror. By making measurements of the signal at many discrete positions of the moving mirror, the spectrum can be reconstructed using a Fourier transform of the temporal coherence of the light. The Michelson or Fourier transform spectrograph was popular for infra-red applications at a time when infra-red astronomy only had single pixel detectors. Imaging Michelson spectrometers are a possibility, but in general have been supplanted by imaging Fabry–Pérot instruments which are easier to construct.

The combination of a Michelson interferometer with a prism monochromator is Köster's interference comparator. In KÖSTER'S INTERFEROMETER as shown in Figure 2 (from [1]), precision Köster's double prism is used as the beam splitter and combiner.

Köster's interferometer has advantages than Michelson interferometer in being one dimension and a compensating plate is not necessary to get the same optical paths.

Köster's interferometer is used for the length measurements in absolute or relative values. For some kind of measurements Köster's interferometer can be used in combination with a laser, with a microscope (V. P. Linnik micro-interferometer).

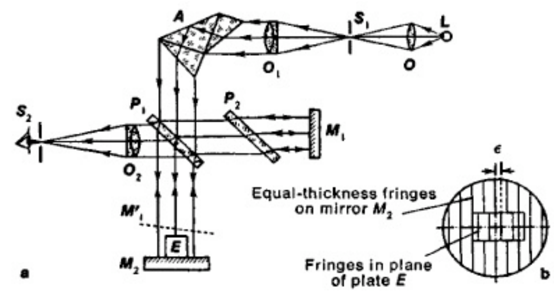

Figure 2. The schematic diagram of Köster's interferometer

Two-beam interferometers, called interferential refractometers, developed for very exact measurements of the refractive index and dispersion of gases. An example of such devices is JAMIN INTERFEROMETER eloped in 1856 by the French physicist Jules Jamin. (Figure 3, from [1]).

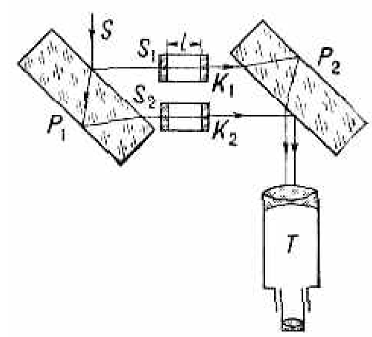

Figure 3. Jamin Interferometer.

The interferometer is made up of two mirrors, made of the thickest glass possible. The Fresnel reflection from the first surface of the mirror acts as a beam splitter. The incident light is split into two rays, parallel to each other and displaced by an amount depending on the thickness of the mirror. The rays are recombined at the second mirror, and ultimately imaged onto a screen.

If a phase-shifting element is added to one arm of the interferometer, then the displacement it causes can be determined by simply counting the interference fringes (e.g., the minima).

Variants of the Jamin interferometer is the MACH-ZEHNDER INTERFEROMETER (Figure 4, from [1]), which is invented over one hundred years ago and still used for many optical measurements and studies of air and gas dynamics.

The Michelson interferometer is a Mach–Zehnder interferometer that has been folded back upon itself. The principal difference is that in the Michelson interferometer, the beam splitting optic is also used to recombine the beams [13].

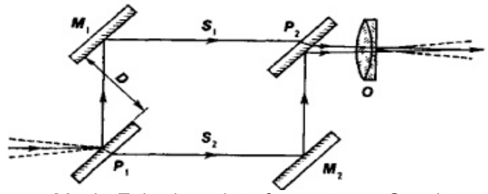

Figure 4. Mach–Zehnder interferometer. Consists of two semitransparent plates P1 and P2 and two mirrors M1 and M2.

Another twobeam interferometer is the RAYLEIGH INTERFEROMETER (Figure 5, from [1]).

The advantage of the Rayleigh interferometer is its simple construction. Its drawbacks are:

• it requires a point or line source of light for good fringe visibility

• the fringes must be viewed with high magnification [14]

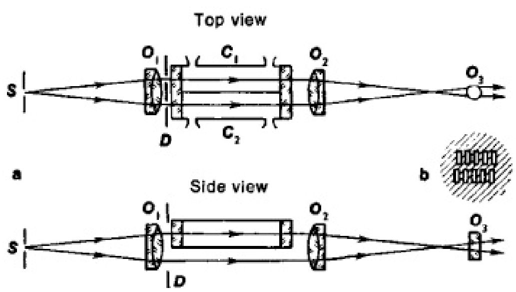

Figure 5. Diagram of the Rayleigh interferometer. Consists of cells C1 and C2, objectives 01, O2, O3.

One of the earliest astronomical interferometers that is built and used is the interferometer was proposed by Albert Michelson in 1890, following a suggestion by Hippolyte Fizeau. (Figure 6, from [1])

The MICHELSON STELLAR INTERFEROMETER is an instrument for measuring angular diameters of astronomical objects, in which a system of mirrors directs two parallel beams of light into a telescope, and angular diameter is determined from the maximum distance between the beams at which interference fringes are observable.

Starlight is reflected by the mirrors *M1*, *M2*, *M3*, and *M4* and produces an interference pattern. The angular resolution between two adjacent maximums is equal to *q=l/D* (Figure 6, b). For any two closest stars at angular resolution *j*, two interference pattern can be observed on the focal plane.

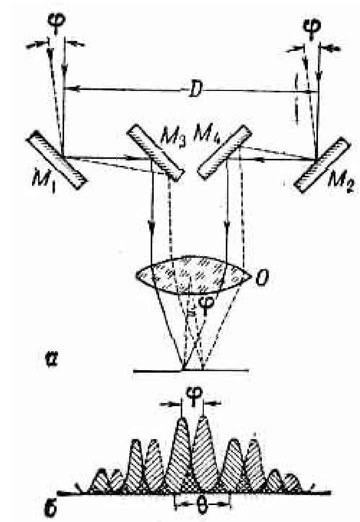

Figure 6. Scheme of the Michelson stellar interferometer

Until now, two-wave interferometers are only talked about, but there are also **multibeam interferometers**.

The quintessence of this kind of interferometers is the FABRY–PÉROT INTERFEROMETER, designed in 1899 by C. Fabry and A. Perot and shown on Figure 7.

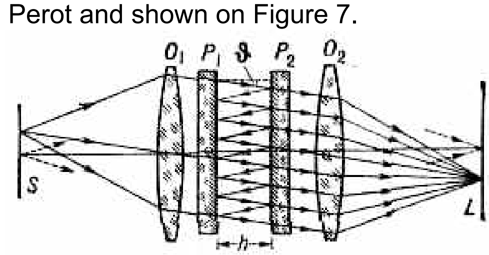

Figure 7. Scheme of the Fabry–Pérot interferometer

The Fabry-Perot interferometer is a significant improvement over the Michelson interferometer. It is typically made of a transparent objectives *O1* and *O2* with two reflecting surfaces *P1* and *P2*, or two parallel highly reflecting mirrors.

The result of multiple reflection from the mirrors, a parallel beam of light incident from the objective O1 forms a large number of parallel coherent beams with a constant path difference between adjacent beams.

The beam of light goes through objective *O1* and after multiple reflection from the mirrors splitting into multiple coherent beams with a constant path difference.

The complete interference pattern in the focal plane *L* of the objective *O2* takes the appearance of a set of concentric rings. The sharpness of the rings depends on the reflectivity of the flats. If the reflectivity is high, resulting in a high *Q* factor, monochromatic light produces a set of narrow bright rings against a dark background. A Fabry–Pérot interferometer with high *Q* is said to have high finesse.

The sensitivity of such a device is improved by the numerous round-trips of the co-propagative and counter-propagative waves. The typical reaction of a Fabry-Pérot interferometer for two kinds of finesse is shown in Figure 8. The higher the reflection coefficient of the reflectors is, the more round-trips in the cavity the waves do, and the finer it is.

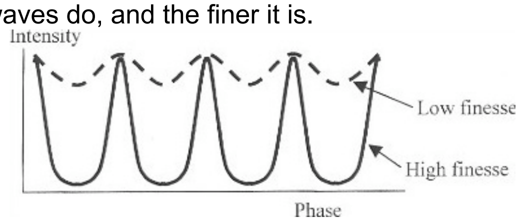

Figure 8. Transmission of a Fabry-Pérot interferometer according to the phase difference and with two different finesses.

Fabry–Pérot interferometers are widely used in telecommunications, lasers and spectroscopy to control and measure the wavelengths of light:

- the most important common applications are as dichroic filters or interference filter whose a very accurate color filter used to selectively pass light of a small range of colors while reflecting other colors.
- an optical wavemeter is a combination of up to five Fabry–Pérot interferometers with a factor of ten difference in $\Delta\lambda$ between any two of them.
- laser resonators are often described as Fabry–Pérot resonators
- used to construct single-mode lasers
- used to make a spectrometer capable of observing the Zeeman effect
- can be used to prolong the interaction length in laser absorption spectrometry techniques.

III. Optical fiber interferometric sensor

Technological benefits of an optical fibers sensing deal with intrinsic properties of materials made of. It allows using it in the harsh conditions of electromagnetic fields and temperature. And here spectrum of its usage is quite wide and many interesting research are possible.

An optical fiber interferometer uses the interference between two beams that have propagated through different optical paths of a single fiber or two different fibers. So, beam splitting and beam combining components are required in any configurations [29]. One of the optical paths should be easily external exposure affected. The measurand can be quantitatively determined by changes in the wavelength, phase, intensity, frequency, bandwidth, and so on.

The current trend of optical fiber interferometers is to miniaturize them for micro-scale applications. Thus, traditional bulk optic components such as beam splitters, combiners, and objective lenses have been rapidly replaced by small-sized fiber devices that enable the sensors to operate on fiber scales. As a best candidate to implement miniaturized optical fiber interferometers, in-line structures which have two optical paths in one physical line have been widely investigated. The in-line structure offers several advantages such as easy alignment, high coupling efficiency, and high stability[31].

Four types of optic fiber interferometers are often used nowadays: Michelson, Mach-Zehnder, Fabry-Perot, Sagnac. Technologies

Some of they are based on hundred years ago invented technologies but fiber optics benefits were an incitement to them for the new applications.

FABRY-PEROT INTERFEROMETER SENSOR

The original version of the Fabry-Perot interferometer (FPI) was described in the first part of the article. For the fiber optic cases, the FPI can be simply formed by intentionally building up reflectors inside or outside of fibers. FPI sensors can be largely classified into two categories: extrinsic and intrinsic [32].

The extrinsic FPI sensor uses the reflections from an external cavity formed out of the interesting fiber (Figure 9a, from [31]). Producing is relatively simple procedure and does not need any high cost equipment. Low coupling efficiency, careful alignment, and packaging problem is disadvantages for extrinsic FPI sensor.

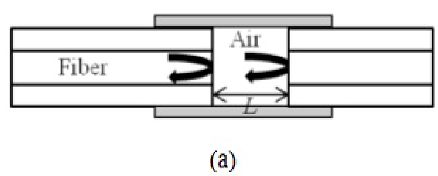

Figure 9a. Extrinsic FPI sensor, the air cavity is formed by a supporting structure

Intrinsic FPI fiber sensors have reflecting components within the fiber itself (Figure 9b, from [31]). The main disadvantage for intrinsic FPI sensors is high cost fabrication equipment for the cavity formation.

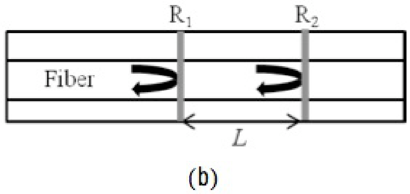

Figure 9b. intrinsic FPI sensor formed by two reflecting components, R1 and R2, along a fiber

When the cavity material is not the fiber itself, intrinsic FPI sensors called extrinsic. For the refractive index measurements of liquids, extrinsic FPI sensors are used because the measurand can easily access the cavity. Complicated laboratory conditions are required for providing such measurements with intrinsic structured FPI.

MACH-ZEHNDER INTERFEROMETER SENSORS

The first versions of Mach-Zehnder interferometers (MZIs) had two separated arms, which are the reference arm and the sensing arm. A beam of light are splitting by a fiber coupler into two directions and then recombined by another fiber coupler. The reference arm is avoid exposure and only the sensing arm is sensitive for the external variations. Then, the variation in the sensing arm induced by such as temperature, strain, and refractive index changes, which can be easily detected by analyzing the variation in the interference signal.

Later the scheme with two independent arms in the MZIs has been replaced with the scheme of in-line waveguide interferometer since the advent of long period fiber gratings (LPGs). Possibility providing simultaneous measurements of several measurands is the advantage of the in-line MZIs.

MICHELSON INTERFEROMETER SENSORS

The main idea behind Michelson interferometers (MIs) is the interference of two beams in separated arms. Which is quite close to the MZIs but there is a difference that each beam is reflected by the end of its arm. In fact, an MI is like a half of an MZI in configuration. Thus, the manufacturing resources and the technological properties of MIs are almost the same as MZIs. The difference is in the existence of a reflector. Simple implementation of sensors array is another advantage of MIs.

MIs are widely used for the measurements of temperature and refractive index of liquid specimens.

An inline implementation of MI is also possible (Figure 10, from [31]). A part of the core mode beam is coupled to the cladding mode(s), which is reflected along with the uncoupled core mode beam by the common reflector at the end of the fiber.

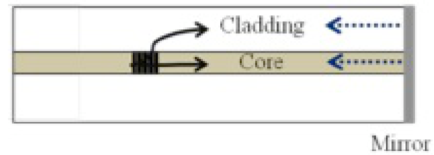

Figure 10. Schema of a compact in-line Michelson interferometer.

SAGNAC INTERFEROMETER SENSOR

Sagnac interferometers(SI) is relatively new technology if compare it with previous interferometers. Their easy-to-build technique, simple structure and robustness leads to using in many sensing applications.

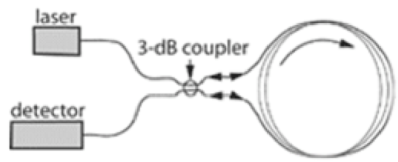

Figure 11. Schema of a Sagnac interferometer. (from osa.magnet.fsu.edu)

Unlike other fiber optic interferometers, the OPD is determined by the polarization dependent propagating speed of the mode guided along the loop.

Main advantage of the SI is the simultaneous sensing capability with the help of other fiber optic devices of other fiber optic devices [33-35].

IV. Applications and Summary

Interferometric sensors are often used for detecting diverse measurands. The most common and simplest one is the strain sensor and this has led to several important classes of sensor.

An especial and very simple case is the measurement of an axial strain that makes possible to perform structural monitoring. For example it can easily be placed in a part made of composite material without compromising integrity.

There are some configurations for a long sensitive area but in practice arrays of sensors are commonly used.

In order to watch infrastructures (like bridges, dikes, etc.) the most common method is using Bragg gratings [17]. However it makes sense to use many structural monitoring applications involving large multiplexed arrays, simply say double interferometers, they are a more convenient design choice than the interferometer [18]. Nevertheless, there are some situations where interferometry is more appropriate. One example is the use of sensing elements to measure length changes in civil engineering structures - air-cavities positioned along the infrastructure. An advantage of using air-cavity sensors is their temperature resistible [19].

It is also possible to measure transversal strains, but they induce birefringence in the fiber, so sensors using polarization modulation are more effective to detect them [20-21].

Interesting results can be achieved for the temperature strain measurements. Multicore fiber can be used to measure bending. Each of the cores is used to form an interferometer. When the fiber is bent, the relative length of the cores changes, revealed as a phase change. Temperature affects each core equally and does not produce a phase shift [22-23].

The same method works for strain and pressure sensing. The most important application of optical pressure sensing is for underwater acoustic measurements in hydrophones for seismic and sonar applications. The effect of pressure is to change the dimensions of the fiber and hence to modulate phase. Development programs are far advanced with many examples of full-scale sea trials [24-25]. These sensors are always deployed in multiplexed arrays.

All the measurands making a strain on the sensitive area are easily detectable, others quantities also are measurable like electric and magnetic fields via magneto- and electro-optic effects [26]. Interferometric techniques enable fine and sensitive measuring but they are limited by the methods you need to resort to in order to get the phase difference without ambiguity. That is why Bragg gratings are still most often used.

The intrinsic sensitivity of fibers to temperature is the drawback in the most cases, but that is useful for the temperature measurements. The Bragg grating is in many cases a preferable technique: it has a simpler structure than an interferometer and there is no problem with fringe-order ambiguity [27]. But interferometry allows achieve the highest resolution [28]. Thus interferometric sensors for special applications continue.

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