Recent Optical Approaches for Quality Control Monitoring in Manufacturing Processes

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Abstract Quality assurance in manufacturing engineering requires precise methods in order to implement quantitative techniques for processes control. Optical methods have proved to be suitable in manufacturing since they present several advantages over traditional approaches such as non-destructive, non-contact, and high speed, among others. For example, laser technologies provide a fundamental tool in optical metrology, and fiber optics offers versatility for multiparameter measurements. Optical methods offer improved technology for quality control monitoring in areas such as materials, pharmaceutical, and chemical.

Keywords Quality control · Manufacturing · Optical sensor

1 Introduction

Optical spectra comprise the ultraviolet (UV), visible (Vis), and infrared (IR) regions (see Fig. 1). UV light is the more energetic region of the optical spectra according to the formula $E = \mathrm{h}\nu$, where E is the energy, h represents the Planck's constant, and ν is the frequency. Since wavelength is inversely proportional to frequency, shorter wavelengths (as UV) contain more energy than regions with larger wavelengths, for

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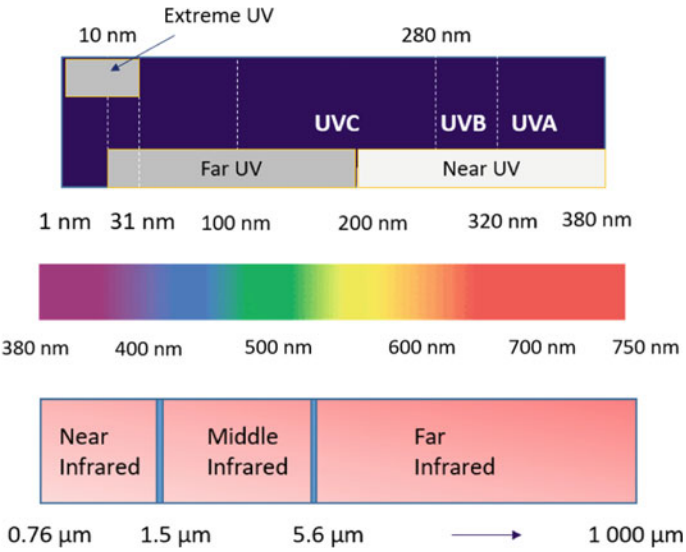


Fig. 1 Optical spectrum regions

example, IR. Interaction of UV light with matter can cause some optical phenomena such as fluorescence which can provide relevant information of a study sample.

Visible light is widely used in optical metrology since its versatility, for example, it can use in low-cost UV-Vis spectrometers to analyze absorbance, reflectance, or transmittance. This can be useful in quality inspection, not only in the optics industry but also in the diverse applications, for example, in the elaboration of food products or the manufacturing process of solar cells. Lasers in visible and near IR regions are currently used for chemical identification by the Raman scattering method. Nowadays the pharmaceutical industry performs quality control procedures based on Raman scattering. Infrared devices are frequently used in optoelectronics for transmission/reception systems. However, there are plenty of techniques for materials characterization by IR light. For instance, Fourier transform infrared (FTIR) spectroscopy typically operates at wavenumbers ranging from 500 to 5000 cm^{-1} (2–20 μm), i.e., middle and far IR. This method is suitable for the identification of functional groups in organic and inorganic substances.

Optical spectroscopy is based on the interaction of light-matter which can provide useful information for quality purposes in manufacturing processes. Figure 2 shows an example of equipment used for characterization by FTIR method. A list of industries and optical methods examples is shown in Table 1.

This chapter aims to study optical techniques, based on non-contact approaches and fiber sensors technology that has been implemented in the last years as a viable alternative to conventional methods for quality monitoring in industrial processes. This work contributes to the analysis of non-contact and high-resolution optical techniques developed for quality control in manufacturing.

Fig. 2 FTIR commercial equipment

Table 1 Optical industry and methods

Industry	Methods
Materials	Diffuse reflectance
Biopharmaceutical	Colorimetry
Food products	Absorbance
Industry 4.0	Photoluminescence
	Raman
	UV-Vis
	FTIR

2 Non-contact Optical Methods for Quality Monitoring

One of the main advantages of optical approaches for monitoring manufacturing processes is the ability to take measurements without physical contact with the corresponding sample. These techniques are often based on lasers or incoherent light sources with a wide spectra emission. Among the optical inspection methods are UV-Vis, FTIR and computer vision as shown in Fig. 3. The main advantages and disadvantages of each technique are shown in Table 2. In this section, the main non-contact free-space optical methods and tools for quality control are reviewed.

2.1 Laser in Manufacturing

Laser is the acronym of light amplification by stimulated emission of radiation; this means that basically it is amplified light. However, it has unique properties, e.g., it is monochromatic, it is highly directional, and all waves that form the laser are in the same phase which is called coherence. These distinctive characteristics make the laser a highly versatile tool, being called a solution in search of problems. Its areas in manufacturing could be divided into two kinds of applications: materials processing

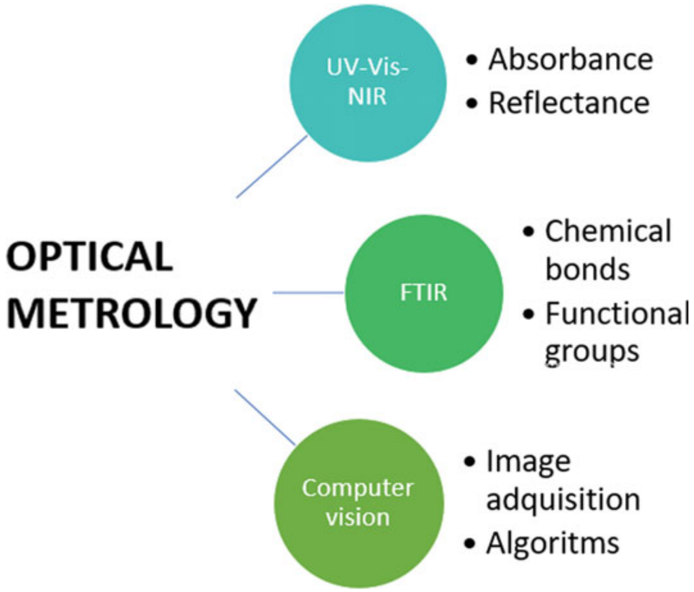


Fig. 3 Optical methods for quality inspection

Table 2 Advantage and disadvantages of optical metrology techniques

Technique	Characteristics
Raman	Pros: It is an accurate method Cons: depends on a weak signal and requires a laser and a spectrometer
Absorbance	Pros: it is a fast and low-cost method Cons: it cannot perform in situ measurements
Reflectance	Pros: it can perform in situ measurements Cons: it requires additional accessory in spectrometer (reflectance probes)
FTIR	Pros: it is appropriate for detecting functional groups present in materials and chemical products Cons: it requires

involving cutting, marking, drilling, welding, and other specialized processes such as surface treatment; and optical metrology which includes technologies such as 3D laser scanners, fiber optics sensors, and free-space optical detectors, among others. In this case, we will be focus on the optical metrology area.

Automated measurement is linked to automated manufacturing processes. Optical technology allows non-contact dimensional measurements with high-quality standards such that required by industries such as aerospace or automotive. A particular technology that has result successful is the 3D laser scanner. There are many advantages of this optical device such as high speed, a resolution in the order of several microns, and ease of use. Although the main areas of application of laser scanners are injection molded plastics, stampings, and castings (turbine blades), and there are emerging fields such as orthopedic implants or rapid prototyping.

2.2 Optical Monitoring of Profiles

Industries related to biomaterial products, renewable energy, or electronics, among others, require accurate methods to measure the surface topography. Although there are well-established technologies such as contact profilometers and laser-based scanning systems, some manufacturing processes require more precise systems. Recently, novel methodologies have been proposed to improve quality control by optical means. For example, in low emittance (low-e) glass manufacturing, optical profile measurements by a novel approach have been carried out (Wu et al. 2018). Low-e glass contains a material such as metal oxide coating transparent to visible wavelengths but highly reflective to infrared radiation. Hence, a quality inspection process of the optical profile is required. In this case, a new method called piecewise polynomial random coefficient (PRC) model was proposed. In this approach, data obtained by laser scanning is analyzed with PRC and multivariate control charts using MATLAB. Through this methodology, shape and intrinsic variations were of optical profiles were accurately measured.

Aerodynamic profiles are fundamental in wind turbine blades. Some of the traditional methods for turbine blades surface measuring include coordinate machine measurements, laser radar technique, and photogrammetry. Although these techniques have shown high accuracy, in general, are complex, slow, and high-cost systems. In a recent work, a novel optical profilometer was developed for quality inspection in turbine blades (Moreno-Oliva et al. 2019). The system is based on the laser triangulation technique (LTT). In this case, a laser diode module (633 nm) and a CCD camera (752 × 480 px) were installed in an XYZ linear stage to perform the surface scanning (Fig. 4). The camera was connected to a computer and images

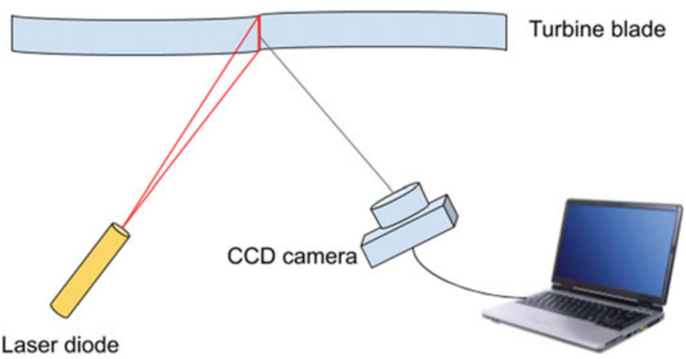


Fig. 4 Scheme for profile measurements of wind turbines (based on Moreno-Oliva et al. 2019)

were analyzed by the Xfoil free software. Results compared with a reference profile showed a high-precision system with a resolution in the order of 0.1 mm. Moreover, this is a low-cost experimental setup that could be adapted to the renewable energy industry.

Optical measurements of surfaces can be difficult in special cases, for example, when a transparent layer is added to the sample. Although several optical techniques could lead to acceptable results, in complicated surfaces, it is appropriated to perform evaluations with different methods. Feng et al. measured surface topographies consisting of a metallic substrate with a transparent coating (Feng et al. 2019). In order to compare with different methods, data were first obtained from scanning electron microscopy (SEM) and optical microscope imaging with focus stacking (FS). In a second stage, areal topography was measured by focus variation microscopy (FVM), point autofocus instruments (PAI), imaging confocal microscopy (ICM), atomic force microscopy (AFM), and coherence scanning interferometry (CSI). In comparison with AFM results, it was found that the CSI method showed better accuracy.

High-precision mechanical parts are demanded in fields such as robotics and mechatronics among others. In particular, gears' quality is critical for the construction of machinery. Coordinate-measuring machines (CMMs) are commonly used for tooth gear inspections. Although this is a highly accurate method, it requires a contact probe which requires a considerable time for measurements. Optical methods are a good alternative since they are non-contact techniques that can perform high-speed measurements. Some optical methods used for 3D reconstruction of gears are based in interferometry, laser triangulation, and Moiré systems. Cheng and Chen developed an optical inspection system to reconstruct a gear tooth surface (Chen and Chen 2019). The system consisted of a halogen lamp as the illumination source, lenses and gratings to produce Moiré fringes and a CCD camera directed to the gear. The approach is based on five-step phase-shifting captured by the camera. Images are processed by MATLAB to carry out a 3D reconstruction of the gear. The authors reported that the difference of the mean values of this Moiré system compared to the CCM method is smaller than 3 ums for three variables: the involute profile, lead profile, and 3D topology.

Optical metrology has been extensively used for non-contact dimensional measurements. Nowadays, optical devices have a resolution comparable with the wavelength of its light source, for example, 633 nm for a He–Ne laser. Recently, Yuan and Zheludev proposed an optical ruler with a resolution of a small fraction of the wavelength (Yuan and Zheludev 2019). The system is based on Pancharatnam-Berry metasurface which creates a diffraction pattern with peaks on the order of subwavelengths. Using a light source of 800 nm, the resolution is about 1 nm. In principle, it is possible to have resolving power of lambda/4000 which could measure atoms. Among the possible applications of this high-resolution optical ruler is the monitoring of microelectromechanical systems (MEMS), measurements of mechanical properties (e.g., the Young modulus), or the inspection of high-precision lenses.

2.3 Materials

Materials have a significant role in manufacture and engineering since electrical, mechanical, or thermal properties among others are key factors in a product's quality. Cement is a high-used product in civil engineering; their physical properties such as strength, consistency, density, or hydration depend on its fabrication process. However, many fabrication processes are empirical, and hence, there is a lack of information in the fabrication method which could vary the results. Optical methods can be used to characterize the physical properties of types of cement, for example, diffuse reflection was used to evaluate the hydration of cement paste (De León Martínez et al. 2015). During the setting process of the cement pass (water added to cement), there is a generation of hydration heat that presents variations related to chemical reactions. Changes in temperature are associated with the stages of the Powers-Brunauers model. It was found that using a He–Ne laser with emission at 633 nm the diffuse reflectance pattern is similar to the temperature pattern (Fig. 5), hence providing important information about the cement hydration process.

Mechanical properties of asphalt determine the quality of pavements. Complex elasticity module has a fundamental importance in asphalt durability. Currently, there are standard methods to determine complex elasticity, and however, conventional approaches require contact devices, e.g., accelerometers or piezo-electric devices, and are limited to low frequencies (30 Hz). Hasheminejad et al. proposed an optical technique to obtain the complex modulus (Hasheminejad et al. 2019). The system consists of a scanning laser Doppler vibrometer (SLDV) and an identification technique based on Timoshenko's beam theory which is associated with the mechanical

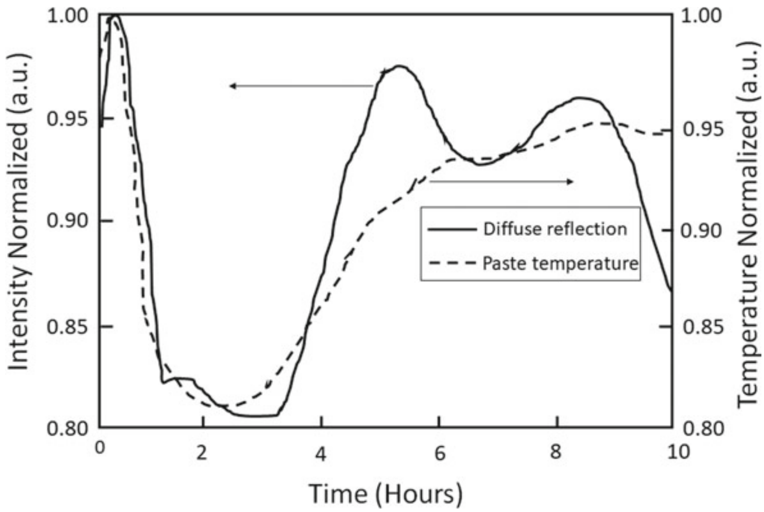


Fig. 5 Temperature versus reflectance on the setting of cement paste. Adapted from De León Martínez et al. (2015)

behavior of a structure under bending. This non-contact method has the capacity of taking measurements at high frequencies (15 kHz). Compared with conventional stiffness tests the SLDV technique reduces the system cost by 20%.

Fibrous porous materials have several applications such as clothing, filters, and medicine among others. Their properties are highly dependent on the orientation of fibers, and hence, automatized systems to evaluate this parameter are required. Computer vision is a suitable method for non-contact optical inspection. In general, this method consists of four stages: image acquisition, image enhancement, image segmentation, and image representation and description. Tunák and Antoch proposed an effective system to inspect the orientation of fibers from image segmentation (Tunák and Antoch 2018). The method is based on the transformation from spatial to frequency domain using the 2D discrete Fourier transform. The Fourier spectrum is transformed into a binary image which direction is related with the real spatial orientation of fibers. To analyze a great sample, the image is divided in small parts that are individually analyzed by the same method, and at the end the total results are represented by a histogram that shows the dominants fiber orientations.

2.4 Automobile Optical Inspection (AOI)

Several industrial manufacturing processes such as automotive parts rely on visual inspection carried out by humans or automated systems. Personal with the required training is often used to perform quality inspection. However, human inspection is limited to low speeds and personal rotation is commonly required. A system for automatic optical inspection was recently proposed for optical inspection of head-up displays (HUD) used in the automotive industry (Ferreira et al. 2017). The system has no moving parts and is intended to be used for regular patterns. This method is based on Fourier filtering and operates below the Shannon–Nyquist criterion which is related to the minimum sampling rate that will not distort the signal information. This system has the advantages of not requiring a high-resolution camera and neither a scanning system.

Quality control can be performed by vibration measurements, for example, in the automotive industry, acoustic waves caused by vibrations are used to evaluate operating conditions of internal combustion engines. However, there are some limitations to implement this method, for instance, a sound isolated space to avoid interference is required, consequently, the quality inspection could affect productivity. Optical vibration measurement is a reliable option for acoustic methods since is acoustic interference-free, and hence, inspections can be carried out in situ. The physical principle of optical vibration measurements is the laser Doppler effect. This effect consists of changes in light wave frequencies corresponding to changes in positions (vibration) as shown in Fig. 6. This method has been used on motors production as inline and end-line process (Polytec).

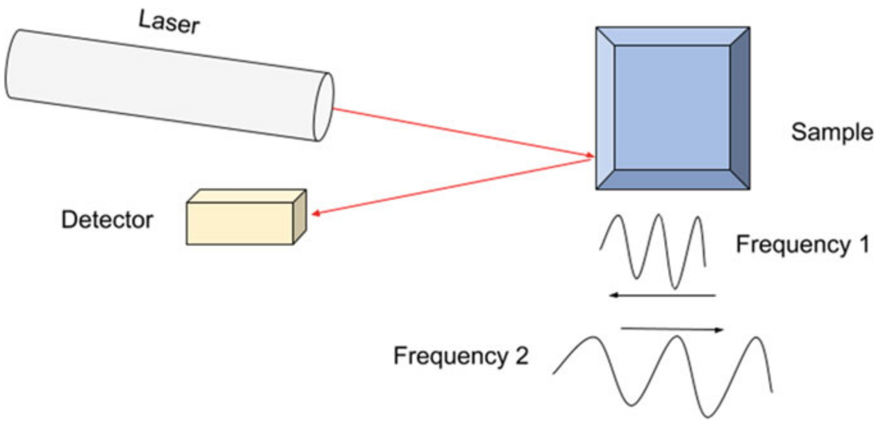


Fig. 6 Laser doppler effect

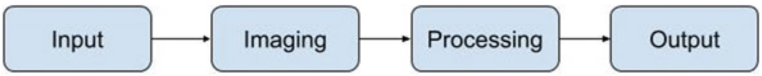


Fig. 7 Machine vision system process

2.5 Advanced Manufacturing

Advanced manufacturing has become a fundamental tool to increase industrial productivity. It is characterized by a high level of innovation and technology involved in the production process. Some of the main areas are virtual manufacturing, assembly technologies, tests and measurements, non-conventional procedures, and monitoring and control of production processes. The advanced manufacturing technologies are robotics and automation, big data, augmented reality, and additive manufacturing.

Some products based on additive manufacturing require high-precision equipment to analyze its surface. Hence, companies such as ZYGO are developing advanced optical metrology equipment, for example, for 3D imaging, a laser Fizeau interferometer-based profilometer is capable of taking 250 million surface topography points per second (Zygo). Other companies such as Keyence offer commercial solutions to quality inspection for example by advanced vision systems (Keyence). Figure 7 shows a scheme of an industrial vision system.

2.6 Food Industry 4.0

The foodstuff industry requires to accomplish high-quality standards to satisfy international import/export norms. Non-contact optical methods traditionally used on

Table 3 Optical quality inspection in agriculture (based on Yeong et al. 2019 and El-Mesery et al. 2019)

Wavelength (nm)	Parameter	Product
400–800	Chlorophyll	Apple
450–1000	Vitamin C	Chillie
600–2200	Moisture	Mushroom
1000–2400	Anthocyanin	Jambu
1200–2200	Maturity	Mango

other industries such as pharmaceutical and chemical manufacturing products have been incorporated in the last years to the food industry. Optical methods can be used to inspect the quality, for example, to measure foodstuff firmness, size, shape, color, substance concentrations, and fat levels, among others. The optical spectrum region often used is between visible and near-infrared (NIR), ranging from 400 to 2600 nm. Some of the optical approaches recently used in quality monitoring of foodstuff include spectroscopy which is based on absorbance, transmittance, reflectance, fluorescence, or phosphorescence; imagology, that consist of a vision system based on a CCD camera and image processing; and spectral imaging, which is a combination of imagology and spectroscopy (Yeong et al. 2019). These techniques are commonly utilized with other tools such as statistical methods or special algorithms to obtain the desired characteristics.

Food product components such as proteins, carotenoids, or chlorophyll, among others, absorb or reflect wavelengths, mainly in the visible-NIR region. Table 3 shows some examples of quality measurements by optical spectroscopy:

Reflectance spectra is a simple and practical method to detect and quantify substances in food products. A general scheme of optical spectroscopy based on reflectance is shown in Fig. 8.

Wang et al. determined the vitamin C concentration in chilies by means of diffuse reflectance spectroscopy (Wang et al. 2011). The studied optical spectrum ranged from 400 to 1800 nm, i.e., visible to near-infrared region. Reflectance data were compared with vitamin C contents obtained with standard methods. In order to obtain a more accurate model, mathematical methods were applied. It was found that the first derivative preprocessing method allows a better correlation between reflectance data and vitamin C concentration.

Optical reflectance has also been implemented to study apple contents such as anthocyanin and chlorophyll (Merzlyak et al. 2003). Pale-green, yellow, and red apples were inspected by visible light ranging from 400 to 800 nm. From this study, it was found that in green and yellow apples, there is a high reflectance correlation at 550 and 700 nm, while in red apples this correlation disappears due to the anthocyanin content. On the other hand, reflectance at 678 nm showed an inverse proportional relation with respect to chlorophyll a and b concentration.

In a recent work regarding as external as internal apple's quality a new approach was proposed (Li et al. 2020). In order to analyze the external appearance, an inline camera installed directly in the production line was used (Fig. 9). The external quality method is based on image processing utilizing the isohypse line extraction

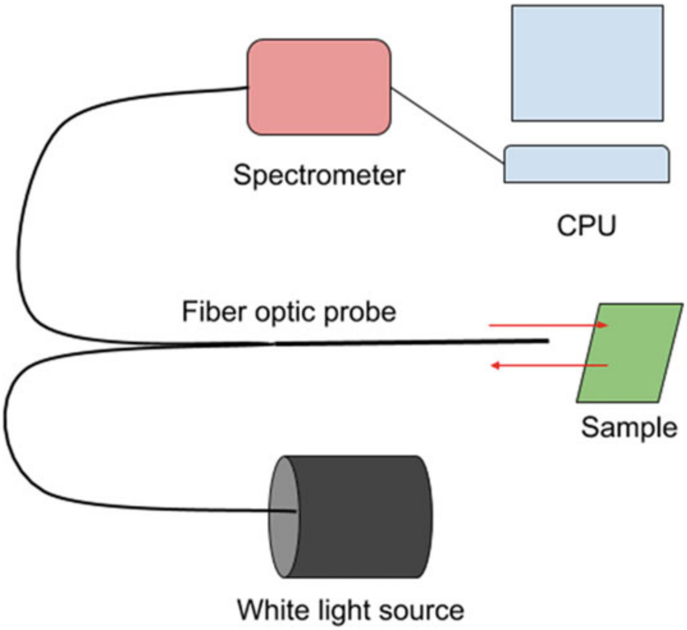


Fig. 8 Optical methods for quality inspection

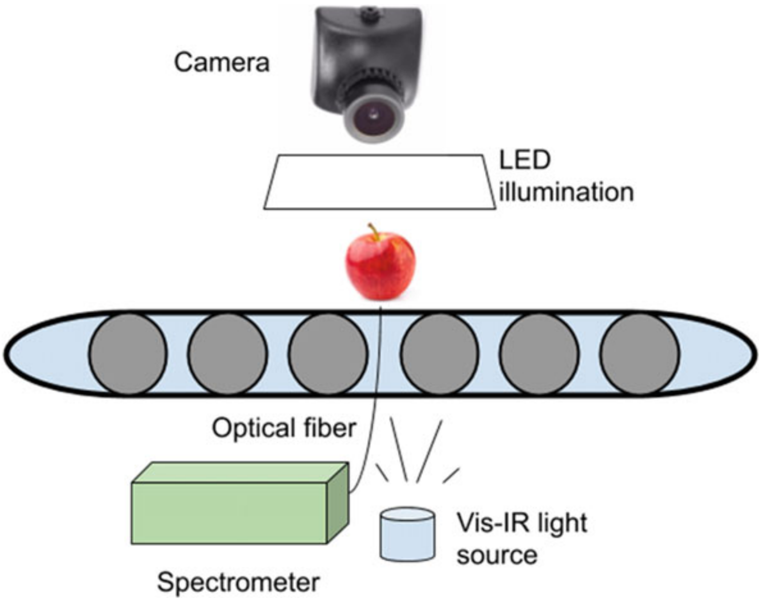


Fig. 9 Inline apple's quality inspection system (adapted from Li et al. 2020)

in combination with marker constraint watershed segmentation (ILE-WSM). This method resolved two issues associated with fruit analysis by vision systems: the light scattering and the uneven brightness in round objects. The detection of external defects showed an accuracy of 97%. Furthermore, internal quality measurements were performed with a spectrometer with fiber optic output. The optical spectrum studied ranged from 600 to 1100 nm. Additionally, the normalized spectral ratio (NSR) method was utilized in order to optimize results. The advantages of this system are compactness and high speed.

Chlorophyll is one of the most studied substances in food products. Chlorophyll plays a key role in the photosynthesis process to convert light in oxygen. Species with a high content of chlorophyll generally present a greenish appearance. This is due to the low absorption at wavelengths around 500 nm, hence the reflection of green light occurs. Besides plants, there are food products that contain chlorophyll. For example, spirulina algae are used as complement food. Figure 10 shows the absorbance spectra of spirulina algae. As can be seen, there are peaks that represents high absorption at 440, 620, and 680 nm.

Traditionally, fermentation evolution is associated with pH levels, hence, contact pH meters are often used. However, test probes are required to take measurements which may contaminate the product. Moreover, the equipment has to be cleaned after each use. Dairy product quality can also be inspected by optical spectroscopy. Arango et al. proposed IR scattering to measure the fermentation process in yogurt based on a fiber optic sensor (Arango et al. 2020). Since IR light scattering showed a correlation with pH, a mathematical model was developed to determine ph levels from 5.2 to 4.6. This non-destructive method is suitable for inline monitoring and could be adapted to similar products.

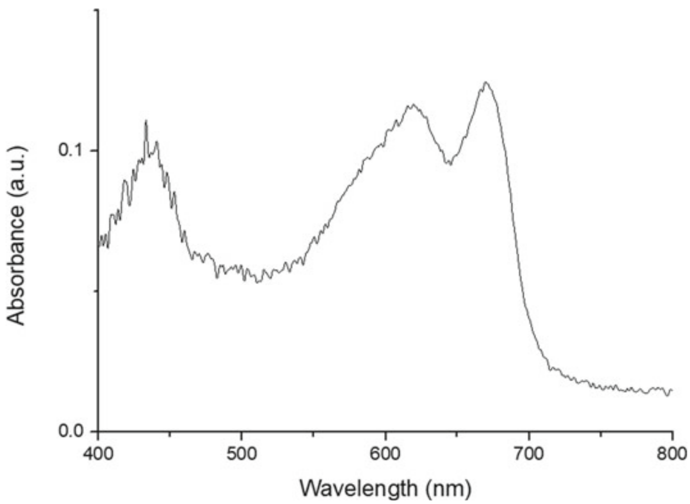


Fig. 10 Spiruline algae absorbance spectra

2.7 Pharmaceutical Industry

One of the manufacturing industries that demands the highest quality standards is pharmaceutical. Therefore, innovative approaches are demanded in order to offer better products. One of the key processes is pharmaceutical cleaning validation. This is important since stainless steel plates, polymer surfaces or instruments, and materials in general, intended to manufacture a pharmaceutical product are required to be free of any substances before being reused. Traditional methods to perform the cleaning inspection task include analytical approaches, for example, the total organic carbon method. Although analytical methods have shown high accuracy, their main drawback is that they are time-consuming since it is required to take a sample to be analyzed in a laboratory which could take several hours. Optical methods such as Raman scattering, phosphorescence, or fluorescence can provide a solution to reduce the time analysis. As shown in Fig. 11, fluorescence occurs when energy is absorbed by matter. In this case, atoms move to ground state to higher energy levels. Atoms tend to return to the ground state which evokes non-radiative and radiative transitions. Energy from radiative transitions consists of photons with a fixed wavelength that depends on the matter energetic levels.

A recent work proposed a laser-induced fluorescence analysis to validate pharmaceutical cleaning (Chullipalliyalil et al. 2020). This method consists of a laser with emission at the deep UV region which produces fluorescence in active pharmaceutical ingredients (API), for instance, Paroxetine, an antidepressant with fluorescent emission at 353 nm. This approach allows for taking in situ measurements to reduce considerably the inspection time. This method allows detecting traces in the order as low as 0.2 $\mu g/cm^2$.

The biopharmaceutical industry requires accurate and high-speed methods for their manufacturing processes. Conventional processes, e.g., mass spectroscopy (M.S.) has some disadvantages that affect productivity. This method requires sample preparation, hence complexity is increased, besides it is a time-consuming method. M.S. may be combined with liquid chromatography to obtain highly accurate data, however, information from this method could be difficult to interpret. Optical spectroscopy is a non-contact analytical method suitable for the biopharma industry. Optical spectroscopy can be divided into electronic (e.g., UV-Vis) and vibrational-based techniques (Raman).

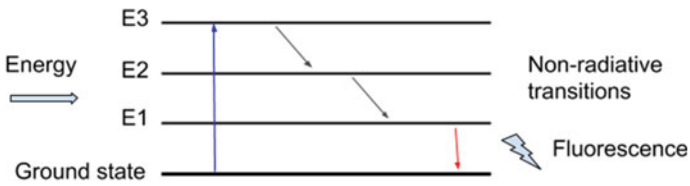


Fig. 11 Fluorescence mechanism

Raman spectroscopy is based on inelastic scattering. These phenomena occur when light interacts with matter and produces scattering. Most of this scattering is elastic and it is associated with Rayleigh scattering. However, a small amount of scattered photons changes its wavelength due to inelastic scattering, which is called Raman scattering. Although Raman spectroscopy has been widely used in forensic and semiconductors, and similar processes can be used in biopharma, it has some limitations. One of them is associated with the weak signal produced as an inherent result of inelastic scattering. Another problem associated with this method is that the emission produced can be difficult to measure when fluorescence is present. Nonetheless, there are alternatives to diminish these problems such as pulsed emissions or enhanced Raman scattering (ERS) that make use of materials such as gold or silver to increase the sensibility.

3 Fiber Sensors

Fiber optics are currently used in telecommunications for Internet transmission; medicine, (endoscopy), or industrial sensing applications. Conventional fiber optics consist of a core surrounded by a cladding (Fig. 12) and are made by silica (SiO_2) although there are also plastic fibers made by polymethylmethacrylate (PMMA) and other polymers. On the other hand, special fibers include double-clad fiber, thin-core fiber, and photonic crystal fiber, among others.

Fiber sensors typically use structural changes or materials coating to produce changes in light traveling inside the fiber due to external variables. For example, long period gratings (LPG) inscribed in fiber enhance its sensitivity to temperature changes. LPG can be fabricated by CO_2 laser (Fig. 13), electric arc, or UV interference patterns. The principle of operation is that periodic perturbations in fiber refractive index, cause rejection bands at punctual wavelengths. This wavelength is affected by external variables.

Among the fiber modifications for sensors are the fiber tapers (Fig. 14). Commonly, fiber is thinned by a method consisting of heating and pulling. Popular heat sources include mini-flames and electric discharge. In fiber tapers, light from the core has close interaction with external media. Fiber sensors based on tapers are

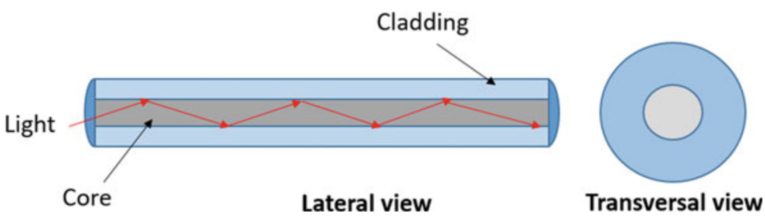


Fig. 12 Fiber optic structure

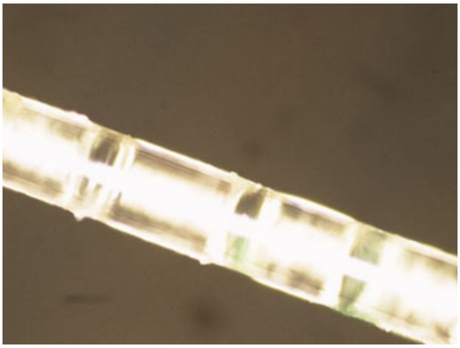


Fig. 13 Long period grating fiber manufactured with laser

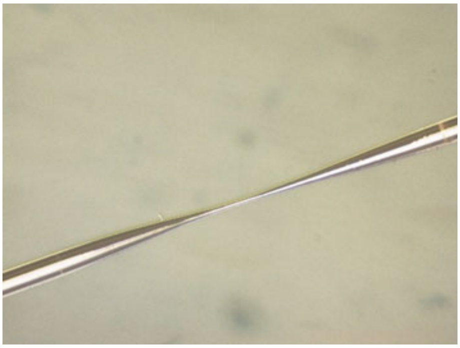


Fig. 14 Fiber taper fabricated by electric arc

used for refractive index or organic/inorganic components. Fiber tapers have also been used for the development of fiber interferometers for sensing applications.

3.1 Fiber Interferometers

Interferometry occurs when two or more signals are out of phase. This phenomenon can be employed in an optical fiber to create sensors. The response of this kind of sensor consists of an interference pattern formed by peaks and valleys (Fig. 15) that can be visualized in an optical spectrum analyzer (OSA). This pattern can be sensible to external variables (pressure, temperature or refractive index, among others) with a corresponding change on frequency or amplitude.

In general, there are four different types of fiber interferometers (Lee et al. 2012):

1. Fabry–Perot.
2. Mach–Zehnder.
3. Michelson.
4. Sagnac.

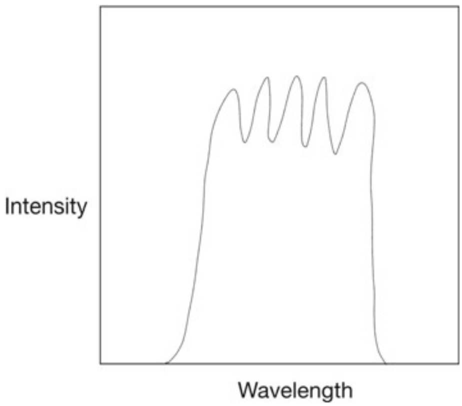


Fig. 15 Interference pattern response of fiber interferometers

The simplest interferometer is the Fabry–Perot configuration. Conventionally, a Fabry–Perot optical cavity consists of a pair of mirrors aligned along an axis. At the end of an optical fiber, a mirror is naturally formed by the interface silica-air which is called Fresnel reflection. Hence, the Fabry–Perot implemented simply with two conventional optical fibers aligned and slightly separated (Fig. 16).

Mach–Zehnder interferometer consists of a difference of optical paths which results in a difference of phase to form the interference pattern. Typically, a super-luminescent led with a wide wavelength spectrum of about 100 nm is utilized as a light source. Light is coupled into an optical fiber connected to a coupler with one input and two outputs, hence, light from on fiber is divided and travels along two different fibers, one of them acting as the sensing arm. Among the elements utilized as sensing fibers are long period gratings or fiber tapers. Finally, light from the two fibers is matched into a second coupler and the output is observed in an OSA. The experimental setup is shown in Fig. 17.

Michelson interferometers-based fiber sensors are often used for temperature or refractive index measurements. In principle, this configuration is similar to the Mach–Zehnder interferometer but it is simpler. The optical arrangement also requires a light source and just one coupler, but in this case, a 2×2 type is needed (2 inputs and 2 outputs). Coupler outputs are connected with optical fibers of different length to induce the phase difference. The end of each fiber has a reflecting element that may

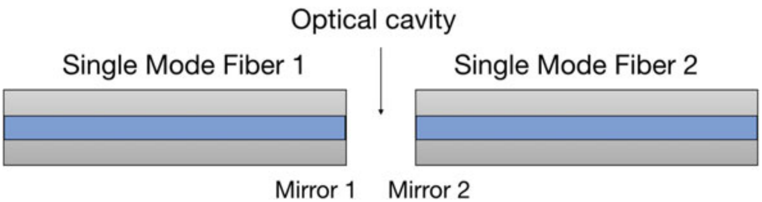


Fig. 16 Fabry–Perot fiber interferometer

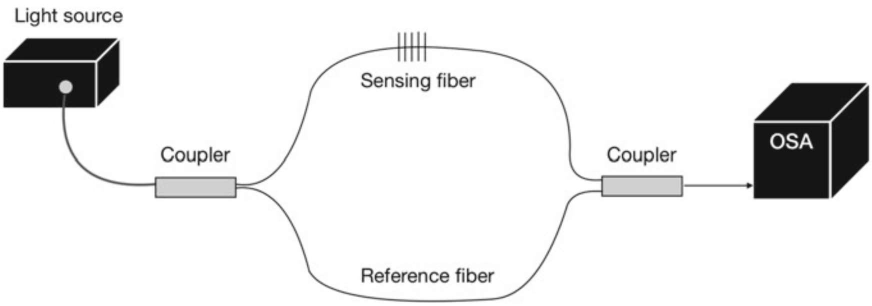


Fig. 17 Mach–Zehnder interferometer

be the Fresnel reflection, a thin film or a FBG among others. A resulting signal returns to the coupler and is visualized in one of the inputs connected to an OSA as shown in Fig. 18.

Sagnac interferometer-based fiber sensor is one of the most practical and easy-to-implement schemes since it is based on a fiber loop. Besides the utilization of a light source and an OSA, this configuration only requires three elements: an optical fiber, a coupler, and a polarization controller (PC) as shown in Fig. 19. The input passes through the coupler and is divided in a 50/50 proportion. Each of the divided signals follows opposite paths and again passes through the coupler to the output. This interferometer usually uses birefringent fibers since it is a polarization-dependent device and can be used as temperature sensors. However, sensing of other variables such as strain or bending, use photonic crystal fibers due to thermal stability.

Although conventional fiber sensors interferometers offer good performance in terms of resolution, robustness, and compactness, most of the schemes need optical couplers which may add an extra space to the sensors besides being expensive. Recently, in-line fiber interferometers had been designed and constructed (Zhu et al. 2012). These types of sensors do not require external elements since the optical schemes are all-fiber. The simplicity and compactness of this kind of fiber sensors make them suitable for industrial applications. Figure 20 shows the principle of

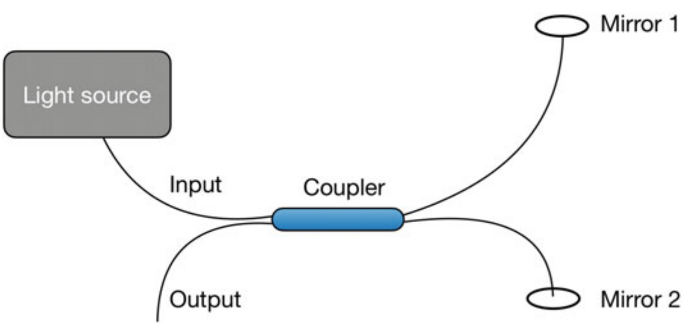


Fig. 18 Michelson interferometer

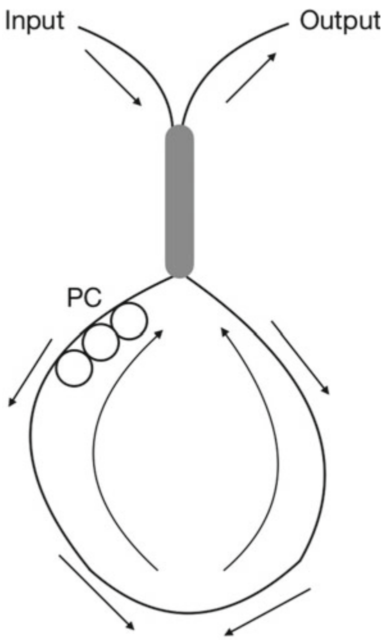


Fig. 19 Sagnac interferometer

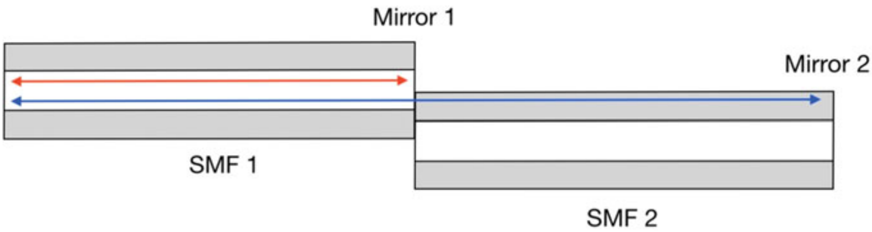


Fig. 20 Inline Fabry–Perot interferometer

operation of an all-fiber Fabry–Perot interferometer. As can be seen, light traveling along the core of an optical fiber (SMF 1) will be reflected at two different distances (represented by red and blue lines), hence interference is produced.

Conventional Mach–Zehnder fiber interferometer is perhaps the least easy setup since utilizing two couplers. However, in-line Mach–Zehnder interferometers can be fabricated from optical fibers spliced with a minimal offset as shown in Fig. 21. Given that light travels along materials with different refractive index (core and cladding) in the middle fiber, both signals become out of phase.

Michelson inline fiber interferometer can be made from just one fiber with a taper and a reflective thin film as shown in Fig. 22. Light is partially coupled from core to cladding due to the fiber taper, hence follows a different optical path and consequently

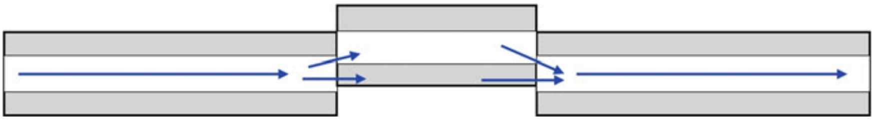
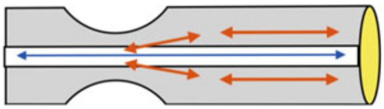


Fig. 21 Inline Mach–Zehnder interferometer

Fig. 22 Inline Michelson interferometer



causes interference. Gold or other highly reflective material is deposited on the fiber end to act as a mirror.

3.2 Fiber Sensors in Quality Control

Fiber sensors have been used in quality control monitoring for several applications. Ghahrizjani et al. developed a low-cost fiber sensor for analysis of engine oil quality (Taheri Ghahrizjani et al. 2016). The sensor consists of a fiber taper, hence light traveling through the core interacts with parameters of the oil such as particle size or contaminants. The detection system uses optical power as interrogation method.

Noiseux et al. proposed a system of two fiber sensors for quality inspection of wine (Noiseux et al. 2004) Monitoring process consisted of a micromachined V-bend fiber to measure refractive index and an absorption sensor based on an air-gap design. The combination of the two fiber sensors allowed to measured sugar contents and color density.

Gases production process requires high standards of quality monitoring. Fiber sensors, in combination with materials (Fig. 23), can be used to detect compounds

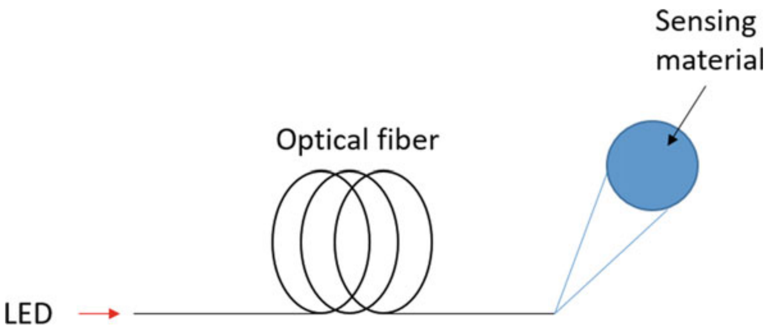


Fig. 23 Fiber sensor based on materials

in gases. Ohira et al. developed a fiber sensor to detect water in industrial gases (Ohira et al. 2015). The sensor is based in a metal organic framework (benzene 1,3,5-tricarboxilate). This sensing material has a blue appearance but change its tone to light blue in presence of wet gases. Sensor response was studied for N_2, Ar, and He with relative sensitivities of 1.00, 0.96, and 1.02, respectively.

Fiber sensors may operate based on different approaches such as interferometers, gratings or Rayleigh backscattering among others. The Rayleigh distributed sensors can be used for monitoring strain or temperature in manufacturing processes by two methods: the optical time domain reflectometry (OTDR) and the optical frequency domain reflectometry (OFDR). OTDR use a similar method that is utilized by radars, i.e., they measure the time a signal travels to a certain point and returns to its origin. Although this is a popular technique, its main drawback is a low spatial resolution. On the other hand, OFDR, although requires an additional step involving the Fourier transform, external variables can be accurately quantified by changes in frequency.

Recently, a fiber sensor based on the OFDR technique was proposed to test printed circuit boards (PCB) strain as part of the quality control in electronics industry (Gomes et al. 2018). In PCB manufacturing, strain excess could cause a future failure in the product even working under normal conditions. Traditionally, PCB strain is measured with foil strain gauges. However, the demand for more components in circuit boards requires more compact sensors. OFDR fiber sensors, besides being compact, are immune to electromagnetic interference which represents an advantage in electronic circuits inspection and can have several sensing points in one optical fiber. The fiber sensor proposed consisted of 390 sensing points distributed along a 1 m fiber. Results showed a similar response compared with foil staring gauges with only a difference of 3.5%. Fiber sensors based on OFDR method could create a two-dimensional map for strain monitoring of PCB with multiple electronic components.

Quality control of fuels is fundamental, especially for companies that produce or distribute gasoline with additions of alcohol (commonly ethanol). This mixture called gasohol is widely used in several countries, and hence, monitoring of the right mixture proportion is required. Although there are chemical methods to analyze gasohol quality, these kinds of tests depend on laboratory studies which delay the results. Moreover, electronic sensing approaches are not suitable for fuel studies for security reasons, i.e., risk of fire. In a fiber, sensor was studied for monitoring of gasohol quality (Rodriguez et al. 2014). The sensor was based on the phenomenon called multimode interference (MMI). This effect is produced when a multimode fiber is spliced to a single-mode fiber in each tip. The original single-mode signal (input) passes through the multimode fiber, which produces interference with periodic focal points as shown on Fig. 24. If the multimode fiber is uncladded, the interference pattern depends on the surrounding media, for example gasohol. Changes in the concentration of a substance produce a variation on the signal wavelength. An output single-mode fiber transmits the signal to an optical spectrum analyzer (OSA) to monitor the substance quality.

Although spectral responses obtained from OSA can provide accurate information in fiber sensors, the main drawback in their implementation is the high cost of this equipment. Photo-detectors convert the amplitude of light signal to a voltage which

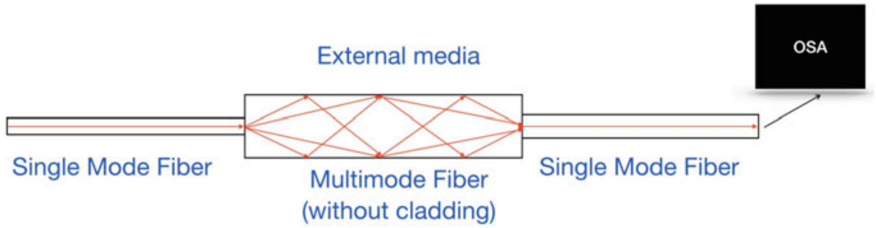


Fig. 24 MMI fiber sensor

can be used as a low-cost alternative in sensors. In a quality amplitude-based fiber, sensor was proposed to determine concentrations of gasoline-ethanol (Aristilde et al. 2019). The device consists of fiber Bragg gratings (FBG) to reflect a wavelength range employed for sensing. The fiber sensor is based on a tilted FBG sensitive to external changes of refractive index that occur with variations in the gasoline–ethanol proportion. These changes are measured by two photodiodes in which output voltages are directly proportional to the percentage of ethanol in gasoline with a resolution of 1.5%. Moreover, this sensor can register temperature variations with a resolution of 0.5 ºC.

A composite is a material made up of more than one substance. Composites are created to improve mechanical properties, for example hardness, strength, ductility, or toughness with respect to conventional materials. These properties make composites suitable for a wide range of applications, mainly in vehicles, aeronautics, and aerospace industries. However, a current challenge is the quality monitoring in the manufacturing process. A conventional technique to fabricate composite parts is called resin transfer molding (RTM). In this method, the composite in the form of resin is emptied into a mold where the material is gradually solidified. Although RTM is apparently a simple process, it requires the monitoring of a uniform distribution of the resin to avoid what is called dry spots which are regions with lack of material. A possible solution is to utilize transparent materials at the top or bottom of the mold to make a visual inspection. However, most composite parts are produced from opaque materials, and hence, sensors are required to monitor the manufacturing process quality. In a recent work (Keulen et al. 2011), a fiber sensor-based experimental setup was proposed to monitor the RTM production process. The monitoring process consists of a fiber optic sensor formed by etched fiber sensors (EFS) and FBG. EFS are formed by uncladder regions of optical fiber that change the intensity of the light traveling through the core fiber depending on the surrounding material. In this way, it can detect the presence of a substance such as a composite resin when it is in contact with the fiber. On the other hand, FBG are used to quantify the strain level (with corresponding shifts on Bragg wavelength monitored in an OSA) that is directly proportional to the material above the sensor. To evaluate the results, Bragg wavelength shifts were studied against strain measured with conventional strain gauge. Results showed a linear response with an R^2 value of 0.999 in a range from 0 to 1700 micro strain units with a resolution of 0.001 nm per microstrain.

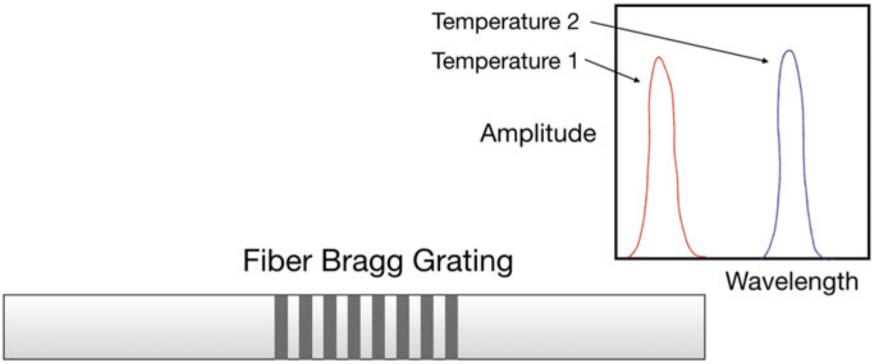


Fig. 25 Bragg wavelength at different temperatures

Metal-mechanic industry is a huge market worldwide. Demand from this industry includes auto parts, oil and aircraft companies. Metal parts manufacturing requires a well-controlled thermal process, since mechanical properties that determine the quality depend on fabrication temperature. Although an option for temperature monitoring is the use of thermal cameras, this technology is relatively expensive and only provides data from the surfaces. Fiber Bragg gratings (FBG) is based on the thermal-optical property of SiO_2 (fiber optic material) to sense temperature. FBG consist of periodic changes in refractive index along a length of optical fiber which cause light reflection of mainly a wavelength called Bragg wavelength. Usually, the light source in a FBG experimental setup is a superluminescent source (SLS). Under temperature variations, Bragg wavelength increase or decrease according the temperature as shown in Fig. 25.

In Alemohammad and Toyserkani (2011), a temperature fiber sensor based on FBG was embedded in a metallic piece for in situ monitoring. To develop this sensor, an optical fiber with FBG was coated with silver nanoparticles to create a conductive thin film. The coated FBG was embedded in a sample part of nickel and steel (with similar mechanical and thermal properties) since area of interest is tools manufacturing.

A layer of tungsten carbide and cobalt was deposited on the steel piece since this material increases the hardness of machining tools. Results showed a linear relation of Bragg wavelength with respect to temperature with a sensitivity of 25.8 pm/ºC.

Embedded fiber sensors have also been implemented to study the manufacturing process of plastics composites. This material is used in aircraft structures, however, its use is limited since more control instruments are needed in their manufacturing process to achieve a uniform quality. In Takeda et al. (2017), FBG were embedded in a thermoplastic composite to monitor the strain and temperature during the fabrication of an L-shaped part. In this case, two FBG were utilized in the positions shown transversely in Fig. 26. A heating monitoring from room temperature to 300 ºC was carried out with a wavelength spectra ranging from 1549 to 1554 nm. Press and demolding processes were also monitored as strain changes reflecting in Bragg

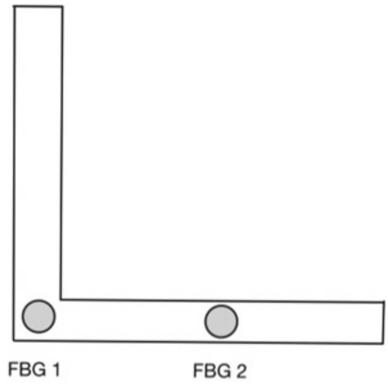


Fig. 26 Embedded fiber sensors based on FBG

wavelength shift. Although, variations in the spectra were minimal (less than one nanometer) which makes it difficult to sense the deformations.

Metal additive manufacturing represents an option to create complex products in a short time. However, there are problems associated with this method such as cracking and delamination which are caused by excessive stress in certain zones. Although there are well established methods to measure the quality of manufactured products, they are designed to evaluate the finished piece and not the manufacturing process. In order to overcome this issue, a smart build-plate based on fiber optic sensors was proposed (Hehr et al. 2020). In this device, the fiber was embedded in the build-plate which is allowed to measure the strain distribution in the manufactured piece. Data from fiber sensing was collected and processed in MATLAB and CAD model data. The prototype was effectively used to monitor quality in a laser-powder bed fusion process.

4 Conclusions

Optical technologies are suitable for quality monitoring in different industrial processes due their characteristics of versatility, compactness, high speed, and high resolution, among others. In general, optical approaches for manufacturing processes can be divided in two areas: free-space measurements involving lasers and contact methods based on fiber optics. Laser-based non-contact methods have been successfully used for quality control of aerodynamic profiles in turbine blades (Moreno-Oliva et al. 2019), 3D reconstruction of gears using interference patterns (Chen and Chen 2019), and in dimensional metrology with an outstanding resolution of 1 nm (Yuan and Zheludev 2019). Moreover, non-contact optical approaches have been used in conjunction with computer vision systems and image processing techniques for inline inspection quality in the food industry 4.0 (Li et al. 2020). Raman spectroscopy and reflectance have been also utilized for quality inspection of food and pharmaceutical products (Chullipalliyalil et al. 2020). On the other hand, fiber sensors are an emerging technology with high potential in monitoring manufacturing process with particular advantages as non-electromagnetic interference issues, distributing sensing, i.e., several sensing points along the same optical fiber and micrometric sizes. Fiber sensors could be based on fiber devices as fiber Bragg gratings, long period gratings, fiber tapers or in fiber interferometers configurations (Fabry–Perot, Mach–Zehnder, Michelson or Sagnac) (Lee et al. 2012). Fiber sensors have been used for quality inspection of oil (Taheri Ghahrizjani et al. 2016), wine (Noiseux et al. 2004), and gases production (Ohira et al. 2015), as well as embedded sensor for inspection of manufacturing processes of metal (Alemohammad and Toyserkani 2011) and composite parts for vehicles and aircraft industries. Based on current optical technology, it is expected an increasing demand in the areas of industrial application for quality monitoring.

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