Application of fiber-optic sensors for the aircraft structure monitoring

Ruslan Zakirov[1,2] **and Feruza Giyasova**[1]

[1] Semiconductor Physics and Microelectronics Research Institute at the National University of Uzbekistan named after Mirzo Ulugbek, Universitet str., building 4, Tashkent 100174, Uzbekistan

[2] E-mail: zrg1980@mail.ru

Abstract. There is a transition from periodic forms of aircraft maintenance to the “on condition” forms performing currently can be observed. Aircraft Health Monitoring system is a very important tool in the formation of “on condition” based maintenance schedule for modern commercial aircraft, which allows collecting and analyzing information about aircraft systems condition. One of the most important components of Aircraft Health Monitoring is the Aircraft Structure Condition Monitoring system, which allows detecting and conditions monitoring of various types of internal damages and mechanical stresses arising in the aircraft structure during its operation. The main advantage of the Aircraft Structure Condition Monitoring system is the absence of its influence on the mechanical and strength characteristics of the aircraft structural elements. Implementation of the system is very important due to constantly expanding possibilities of using composite materials in aircraft structure. This article proposes a method for implementing Aircraft Structure Condition Monitoring system by using fiber–optic sensors. A feature of the proposed system is the integration of sensors into the structure of the aircraft. A review and analysis of the applicability of photodetectors for the proposed system is also given.

1. Introduction

A significant contribution to the issue of flight safety may be created by onboard systems of a new generation, which not only monitor the technical condition of the aircraft, but can also predict the moment when a problem unit will require replacement. Such systems can diagnose episodic failures which can appear during flight. The transition from the routine maintenance to aircraft health monitoring (AHM) expected soon. These systems predict failures and degradation of unit performance and automatically create maintenance and repair schedule, which in the long term can lead to a complete rejection of periodic forms of maintenance.

Increasing of composite materials using in aircraft structure, including in aerospace engineering, as well as in other areas requiring increased reliability of structures [1], makes the task of structure health monitoring (SHM technology – one of the most significant part of AHM technology) very important. The creation and application of “smart” materials, including those with adaptive properties, also requires the use of a more advanced system of SHM. Such a system should promptly detect defects in the structure, adequately respond to their presence and issue appropriate influences or recommendations.

One of the most promising approaches is the using of fiber–optic sensors as part of the structure health monitoring system. Fiber–optic sensors have the following significant advantages over classical ones:

- low weight;
- high sensitivity;
- electromagnetic compatibility;
- possibility of networking, as well as multiplexing;
- compatibility with composite structures.

A great advantage of fiber optic sensors is also the ability to measure many parameters necessary for aircraft structure diagnostics:

- deformation, pressure and force;
- electric and magnetic fields;
- sound and vibration;
- pH and viscosity; etc.

2. Fiber optic sensor classification

Fiber optic sensors use Interferometry principles of operation and divided as follow:

- Fabry-Perot interferometer;
- Michelson interferometer;
- Sagnac interferometer;
- Mach-Zender interferometer.

Sensors can also be built on a grating basis. These sensors are divided as follow:

- Long period grating (LPG);
- Fiber Bragg grating (FBG);
- Tilted Fiber Bragg grating;
- Chirped Fiber Bragg grating.

Distributed optical fiber sensor (DOFS) are also used in SHM. The following principles are used in these sensors:

- Raman scattering;
- Rayleigh scattering;
- Brillouin scattering.

Let us consider the described types of fiber optic sensors in detail.

2.1. Interferometric sensors

The most widespread items are the fiber–optic interferometers of Mach-Zehnder, Meikelson, Fabry-Perot, Sagnac. Using of a resonator in the path of transmitted radiation is a distinctive feature of interference sensors. Combination or separation of radiation is performed by using fiber–optic splitters and mirrors, which are dielectric coatings, including multilayer ones, applied to the end of the fiber.

Due to the emerging phenomenon of light interference, it is possible to determine the corresponding parameters of the material or processes occurring in it [2]. This method makes it possible to measure ultra–small deformations with a high frequency, which makes it possible to register acoustic waves in the material.

The resolution of Fabry–Perot sensors is up to 0.000015%, the range of working deformations is ±0.1% and temperatures are from –40 to +250°C [3]. Fabry–Perot sensors have small linear dimensions as a rule from 1 to 20 mm long. With these sensors it is possible to register both ultrasonic vibrations and acoustic emission. To detect structural damage in composite aircraft structures, it is possible to use such sensors for recording acoustic waves.

2.2. Fiber Bragg Sensing Technology

The sensing element of a point fiber–optic sensor is a fiber–Bragg grating (FBG). A fiber Bragg grating reflects radiation at a certain wavelength and is transparent for other wavelengths. This selective reflection is achieved by creating a periodic structure in the fiber core. The reflected signal is recorded by the receiving equipment.

An external influence on the FBG leads to a change in the parameters of the Bragg grating, which in turn leads to a change in the wavelength reflected from it. This change can be used to make decision about the required characteristics – deformation, temperature, pressure.

FBG–based sensors do not have any electronic components, i.e., they are passive. This opens wide possibilities for the using of such sensors in hazardous areas and in areas with strong electromagnetic interference.

Multiple Bragg gratings can be created on a single fiber. Each of them will reflect radiation at its own wavelength. This allows us to create a distributed monitoring system with wavelength multiplexing.

Advantages of FBG–based sensors:

- wide range of measurements;
- ability to integrate the sensor into the control object;
- explosion and fire safety;
- easy way of multiplexing;
- insensitivity to electromagnetic interference;
- resistance to the environmental impact [20].

2.3. Distributed Sensing Technology

In the distributed measurement method, the fiber optic cable itself is a distributed sensing element, that is, a sensor (Figure 1). The method is based on registration of stimulated Raman scattering. The scattered signal is recorded by the receiving equipment [4].

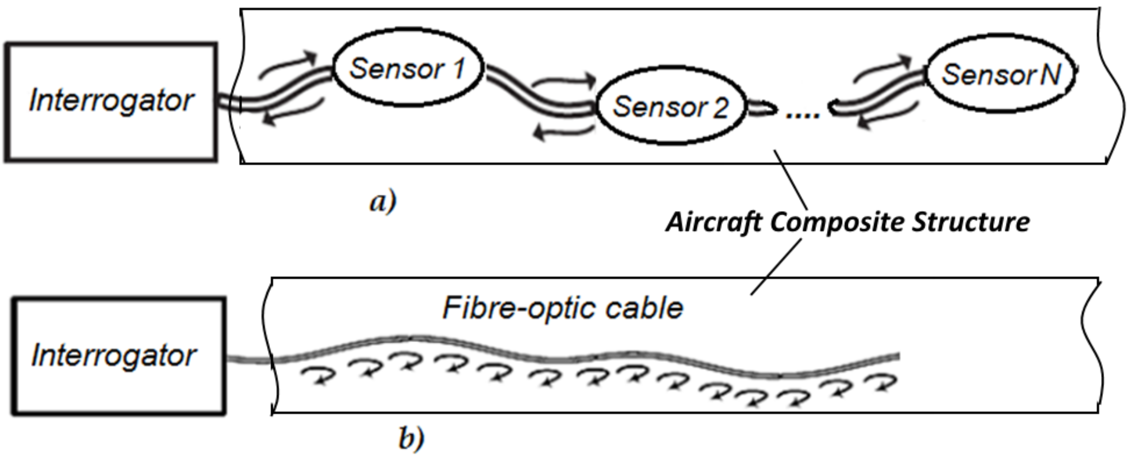


Figure 1. Fiber optic sensor system: *a)* – fiber–optic sensors based on a Bragg grating; *b)* – distributed fiber–optic sensors

There are several ways to process signals when using a distributed sensor: Optical time–domain reflectometry (OTDR), Raman optical time–domain reflectometry (ROTDR), and reflectometry based on Brillouin scattering (Brillouin optical time–domain reflectometry – BOTDR).

The OTDR method is based on Rayleigh scattering caused by the transmission of light through an optical fiber. The scattered signal is registered by a photodetector.

The ROTDR method is based on Raman scattering. In this case, spectrum components called Stokes and anti–Stokes components that were missed in the emitted signal appear in the scattered signal. By the ratio of the intensities of these components, it is possible to determine the temperature of the fiber at any point. The BOTDR method is based on Brillouin scattering. The deformation and temperature of an optical fiber can be determined by the frequency change of the scattered light described in details in [5].

The properties of the fiber–optic cable can be varied over a wide range, resulting in fiber with properties that meet the requirements of the application.

3. Application of fiber optic methods for aircraft structures integrity of monitoring

3.1. Acoustic emission

Currently, there is a continuous trend towards an increasing of using of composite materials in aircraft construction. However, it is much more difficult to detect damage in composite structures than in metal ones. Cracks and delamination in the material can occur without visible damage to the surface layers. By monitoring acoustic emission, it is possible to detect the appearance of such internal damage by analyzing the sound waves emanating from them, and also to determine their location. Conventional piezo–acoustic sensors are not very useful for the aircraft structure control due to their sensitivity to electromagnetic interference, massive connecting cables, complexity with multiplexing and impossibility of using in hazardous areas.

Using of fiber–optic distributed systems for monitoring acoustic emission is free from the above disadvantages. Localization of the source of acoustic emission is also possible. For these purposes, in [6], one of the methods of artificial intelligence was applied, namely, the Support Vector Regression (SVR) method.

3.2. Localization of defects

Structural health monitoring is critical for loop safety and predicting the life-of-structure – especially in aviation and aircraft production industry. Among the various methods, Lamb waves have great opportunities for detecting damage and defects due to their sensitivity to small damage and the possibility of propagation over relatively large distances.

Using of fiber–optic sensors based on Bragg gratings for detecting Lamb waves, including a phased array, is shown in [7]. Such sensors have small size and weight, and can operate in hard operating conditions – at high humidity, under water, at high temperatures, and can also be built into the structure of a composite material. It is also possible to generate sound using optical fiber and a laser source.

3.3. Temperature measurement

Along with the monitoring of aircraft structure mechanical stresses, temperature measurement is one of the main tasks solved using fiber–optic sensors in AHM. Temperature measurement is performed using both fiber–optic sensors based on Bragg gratings and distributed fiber–optic sensors [8].

Typical applications for fiber optic temperature sensors are fire alarm systems, thermal monitoring of power cables and power lines, temperature monitoring of chemical processes, and pipeline leak detection. It is also possible to embed such a sensor into composite structure and measure its temperature field.

3.4. Stresses and deformations monitoring

Monitoring of mechanical stresses inside structures is one of the most frequently solved problems using fiber–optic sensors [9]. Currently, the most accessible are sensors based on a fiber Bragg grating, the principle of which is based on changing its period under the influence of external factors. This change is caused both by a change in the deformation of the lattice and by a change in its temperature. Without information about the temperature, it is impossible to give an unambiguous assessment of the deformation type and size.

Using of an FBG embedded in a composite material as a sensor is associated with certain difficulties associated primarily with the fact that both axial and radial components contribute to the resulting deformation of the lattice.

According to the values of stresses inside the structure, it is possible to assess its shape, which is especially important for use in "smart" structures [10]. In the aircraft production industry using of "smart" designs will make it possible to create unique devices for the active control of aerodynamic flows, which will significantly increase the efficiency and safety of aircraft composite structure diagnostics technology.

A femtosecond laser can also be used to create various structures inside a fiber – waveguides, Bragg gratings, interferometers, spectrometers, polarizing elements, mirrors, etc. (Figure 2). These structures may have different orientations and can help to solve the problem of three–dimensional voltage measurement and determination of the shape of the structure using a fiber Bragg grating.

Due to the waveguides created inside the fiber, it becomes possible to output radiation not only through the ends of the fiber. This opens up wide possibilities for creating distributed networks of such sensors with different characteristics.

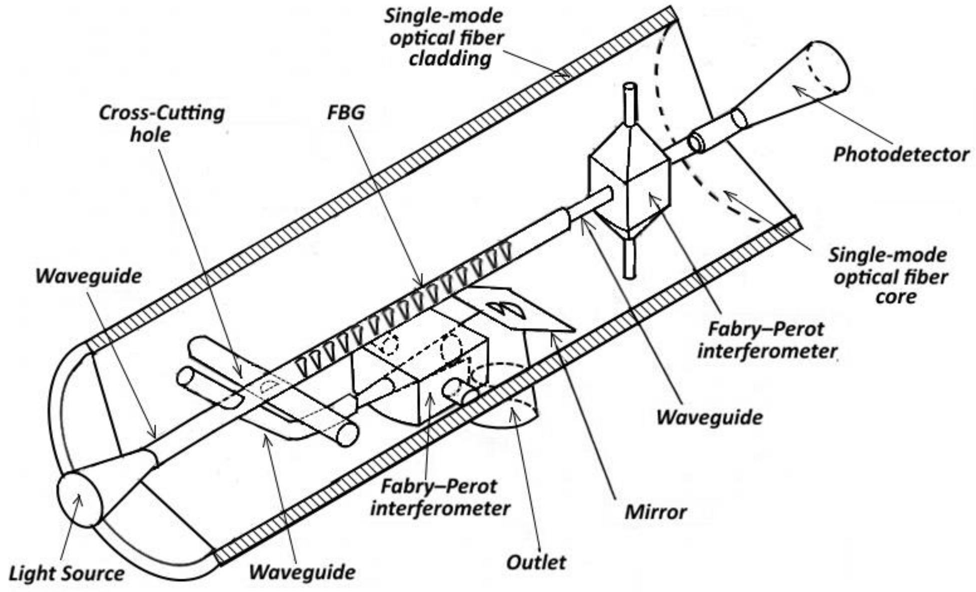


Figure 2. Variants of structures formed in fiber using a femtosecond laser
Source:https://dspace.susu.ru/xmlui/bitstream/handle/0001.74/29171/2019_464_vakhitovadv.pdf?sequence=1

The complex development of such systems can lead to the creation of a fiber–optic sensor that does not require an interrogator or contains it inside the fiber. Such a sensor can be built into the material and not have any physical connections with the outside components, i.e., there will be no need to bring the sensor outside and process the results of its operation on bulky equipment, which will improve the technology and reduce the cost of using such sensors. The measurement results will be transmitted over a radio channel, which will also be built into the fiber.

4. Analysis of photodetectors for using in SHM system

Engineers designing optoelectronic devices for optical signal detection and transmission recently started to pay particular attention to the development of photodiodes operable in the spectral range of 0.85 and 1.31 µm. Photodiodes for the above spectral ranges are mostly designed and manufactured on the basis of gallium arsenide, indium phosphide, cadmium sulfide and telluride, as well as on solid solutions based on them. For example, photodiodes with a p–n junction based on gallium arsenide make it possible to obtain photosensitivity in the spectral range of 250–900 nm. Review of the existing experimental results in [11] indicates that the maximum photosensitivity in the gallium arsenide photodiode occurs near 800 nm. The maximum photo–response reaches 0.5 A/W, and at 300 nm appeared to be 0.04 A/W. The material most suitable for the spectral range of 0.9–1.7 µm is zinc doped indium phosphide with a photo–separating p – n junction.

In heteroepitaxial N^+–InP/n^0–$In_{0.53}Ga_{0.47}As$/n^+InP photodiode structures low capacitance values (1.6 pF at 5V) and high photosensitivity at a maximum of 0.9 A/W were reported [12]. The current in the measuring circuit did not exceed 100 µA. In_xGa_1–xAs is believed to be the most suitable material for high–speed photodiodes designed for fiber–optic communication systems operable in the spectral range of 1.3 and 1.55 µm.

It is also important to ensure the highest possible sensitivity, minimum capacitance, minimum dark current, minimum equivalent noise power while choosing a photodiode for the required spectral range.

To solve this issue, researchers apply methods of manufacturing photodiodes in the form of mesa structures as well as building corresponding guard ring to rectifying transitions, even though the above techniques are not widely believed to be very effective.

The most suitable photodetectors for fiber optic systems are semiconductor p–i–n and avalanche photodiodes (APD). In p–i–n–photodiodes, a layer with intrinsic conductivity (i–region) is usually introduced in between layers with polar conductivity, and when the reverse bias voltage is applied to this region, the region will subsequently be depleted (less free carriers), whereas the strong electric field in it will accelerate carriers that will be generated as a result of absorption of light. They are more sensitive due to reduced losses from recombination. The barrier capacitance is negligent, due to which a satisfactory frequency characteristics are provided. These diodes require a small reverse bias voltage (5V or even less), which promotes their predominant application in LANs and other terminal devices.

Avalanche photodiodes have internal amplification capacity and differ from p–i–n photodiodes by the presence of another additional layer. At high reverse bias voltages (near 100V), a strong accelerating field is formed inside them, and avalanched multiplication of charge carriers occurs, i.e., an increase in the photocurrent. These devices are characterized by high sensitivity, high gain and high speed, however, their widespread application is hindered by their complexity, high cost, high operating voltages, the need to stabilize voltages and temperatures and they can operate only in the mode of weak signal amplification.

– It's important to mention that at significantly larger areas of 4–40 mm^2, when the following conditions are met:

– material of the base region was properly selected;

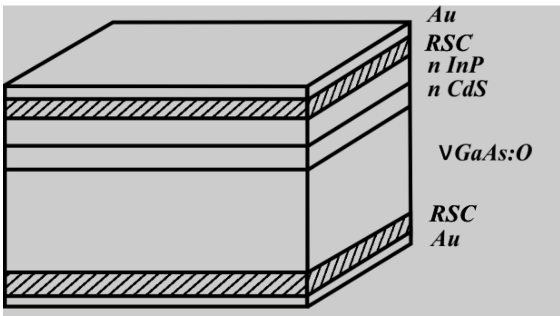
– physical properties of the formation of the metal – semiconductor transition in gallium arsenide were applied;

– integration of the metal – semiconductor transition with a rectifying p – n junction was ensured during the technological cycle;

– the closure of adjacent potential barriers was achieved one could obtain photodiode structures with low dark currents (10–(6–7) A/cm^2) and high photosensitivity (2 to 20 A / W) [9], which are designed to detect optical signals [13].

Meanwhile, experts in photosensitive devices witnessed increased application of film structures, since this technology allows relative ease in building the films with required dimensions and the technique itself is easy to deploy in comparison to the technique of bulk structures.

In the aircraft SHM systems using of a multilayer photosensitive Au–νGaAs:O–nCdS–nInP–Au–structure based on gallium arsenide with embedded potential barriers photodetector (Figure 3) is proposed.



The Au–translucent rectifier layer; RSC–region of space charge; nInP–sprayed layers of indium phosphide and nCdS–cadmium sulfide with a thickness 0.4 μm; νGaAs:O is gallium arsenide substrate semi–insulating with a thickness of 350 μm.

Figure 3. Cross–section of photosensitive multilayered semiconductor Au–νGaAs:O–nCdS–nInP–Au of structure

Conclusion

Using of fiber–optic sensors for aircraft structure health monitoring, including structures made of composite materials, is very promising. The increasing number of aircraft elements from composite materials, as well as the creation and use in the future of "smart" materials and structures, including those with adaptive properties, will require continuous improvement of the system for monitoring the conditions of the structure, as well as assessing its geometric shape, residual life and other parameters.

Promising complex systems created inside the fiber, combining elements of electronics, optoelectronics, micromechanics and photonics, will radically change the ways of using fiber–optic sensors in aviation materials and structures.

References

[1] Zhu P, Xie X, Sun X and Sotoac M A 2019 Distributed modular temperature–strain sensor based on optical fiber embedded in laminated composites. *Composites Part B: Engineering.* Vol 168 pp 267-273

[2] Yu H, Wang Y, Ma J, Zheng Z, Luo Z and Zheng Y 2018 Fabry–Perot Interferometric High–Temperature Sensing Up to 1200°C Based on a Silica Glass Photonic Crystal Fiber. *Sensors.* Vol 18 273 p

[3] Yoshino T, Kurosawa K, Itoh K and Ose T 1982 Fiber–optic Fabry–Perot interferometer and its sensor applications. *IEEE Journal of Quantum Electronics.* Vol 4 pp 626-665

[4] Hartog A H 2017 An introduction to distributed optical fiber sensors. CRC Press, 442 p

[5] Wei H, Zhao X, Kong X et al. 2014 The Performance Analysis of Distributed Brillouin Corrosion Sensors for Steel Reinforced Concrete Structures // Sensors. Vol 14 pp 431-442

[6] Sai Y, Zhao X, Hou D and Jiang M 2017 Acoustic Emission Localization Based on FBG Sensing Net–work and SVR Algorithm // Photonic sensors. Vol 7 No 1 pp 48-54

[7] Tian Z, Yu L, Sun X and Lin B 2019 Damage localization with fiber Bragg grating Lamb wave sensing through adaptive phased array imaging // SAGE Publications Structural Health Monitoring. Vol 17 Issue 1 pp 334-344

[8] Yu F and Okabe Y 2017 Fiber–Optic Sensor–Based Remote Acoustic Emission Measurement in a 1000°C Environment // Sensors. Vol 17 pp 1-14

[9] Ramakrishnan M, Rajan G, Semenova Y and Farrell G 2016 Overview of Fiber Optic Sensor Technologies for Strain/Temperature Sensing Applications in Composite Materials // Sensors. Vol 16 pp 1-27

[10] Sun J, Guan Q, Liu Y and Leng J 2016 Morphing aircraft based on smart materials and structures: A state–of–the–art review // Journal of Intelligent Material Systems and Structures. Vol 27 (17) pp 2289-2312

[11] MacDougal M, Hood A et. al. 2011 Part of the SPIE Infrared Technology and Applications XXXVII. V 8012 No 21

[12] N K Dhar, R Dat and A K Sood 2013 Optoelectronics – Advanced Materials and Devices. S L Pyshkin, J M Ballato – January, 2013 pp 149-186

[13] Karimov A V, Yodgorova D M and Abdulkaev O A 2011 Physical principles of photo–current generation in Multi–Barrier Punch–Throungh–Structures Second chapter of book "Photodiodes – World Activities in 2011" edited by Jeong–Woo Park. – InTech, pp 23-36 [ISBN: 9789533075]