A concept of microwave photonic sensor systems based on addressed fiber Bragg gratings

A Zh Sakhabutdinov¹, O G Morozov¹, G A Morozov¹, R Sh Misbakhov², A A Kuznetsov³, I I Nureev¹

¹Professor, Kazan national research technical university n.a. A.N. Tupolev-KAI, Kazan, Russia
²Docent, Kazan state power engineering university, Kazan, Russia
³Docent, Kazan national research technical university n.a. A.N. Tupolev-KAI, Kazan, Russia
E-mail: AZhSakhabutdinov@kai.ru

Abstract. The main drawback of the modern microwave photonic sensor systems is the absence of addressable fiber optic sensors, as a rule, based on fiber Bragg gratings, which leads to the need to build complex sensing systems and interrogators that are tuned to different wavelengths or combined into groups according to the common central wavelength. We proposed addressed fiber Bragg gratings, which structures can be realized in two variants: with two symmetrical phase π-shifts in one grating (2π-AFBG) or two serial gratings with different Bragg wavelengths (2λ-AFBG). Their common feature is difference frequency between two phase shifts or two gratings, which is lying in microwave range and defining its address, wherein addressed gratings have the same Bragg or central wavelength. So, their interrogation can be realized in microwave range by evaluation of envelope characteristics of beating signal on addressed frequency components. A new microwave photonic sensor systems class is called “MicroWave Photonic Sensor Systems based on Addressed Fiber Bragg Gratings”. The concept of new class sensor systems is presented. The sets of analysis and synthesis problems, measuring level design for point, few sensor and multi-sensor variants, and principle of joint field of multiplexed sensors construction for system are considered. When implemented, the interrogation speed can be increased to hundreds of MHz, the resolution is up to units of Hz, which is determined by the parameters of microwave (not optical) processing, cost of system, its exploitation and design complexity are drastically decreased.

1. Introduction

The scientific and technical problem of improving metrological, design, operational, and cost characteristics, as well as expanding the functionality of microwave photonic sensor systems (MWPSS) is extremely relevant task which require an effective solutions. MWPSS, as a rule, are built using multiplexed fiber-optic sensors (FOS) based on fiber Bragg gratings (FBG) [1].

A common analysis of the MWPSS characteristics, FOS, used in them, the methods of its multiplexing and interrogation, as well as, the types of probing signals and the methods of their measurement conversion, allowed to propose a new class of sensor systems for solve the task above. The established arguments and requirements for a construction of new MWPSS, based on results of the analysis, clearly indicate the need to consider a possibility of creating them using addressed approaches.

Known addressed approach to interrogation in sensor networks is the use of optical code division multiplexing (OCDM) [2, 3], using which an array of sensors is probed with a pseudo random binary sequence (PRBS) to correlate the reflected signal from each sensor with an instant code sent to the network. This method uses super-structured FBGs, with an optical code recorded in each of them, designed to decrypt (identify) and obtain orthogonality with respect to their neighbouring sensors in the
network. In this case, the orthogonality of the codes between adjacent sensors allows them to overlap in the same operating range, thereby increasing bandwidth utilization in the network. One of the simple ways to achieve optical structures with mutual orthogonality between them is to use Slepian’s discrete elongated spheroidal functions [4].

Despite the advantages, this method is very difficult to implement. The interrogator should be able to restore both quantities (amplitude and phase) of the frequency response. Therefore, special synchronization is required between the source and the processor of the reflected signal, which in the end can be understood as a special case of multiplexing in the time domain with its shortcomings in the speed of interrogation of sensors, measurement errors, and complexity of implementation.

Given this factor, we will look for approaches to the creation of addressed sensors based on the results of the development of poly-harmonic frequency microwave photonic methods of FBG interrogation [5–10]. Our proposed approach is addressed fiber Bragg grating. AFBGs are the Bragg structures which can be realized in two variants: with two symmetrical phase \( \pi \)-shifts in one FBG (2\( \pi \)-AFBG) or two serial FBGs with different Bragg wavelengths (2x-AFBG). Their common feature is difference frequency between two phase shifts or two FBGs, which is lying in microwave range and defining the address of AFBGs, if all of latter have the same Bragg or central wavelength. So, the interrogation of AFBGs can be realized in microwave range by evaluation of envelope characteristics of beating signal on addressed frequency components. A new MWPSS class is called “Microwave Photonic Sensor Systems based on Addressed Fiber Bragg Gratings” (MWPSS based on AFBG).

2. **Sets of analysis and synthesis problems for MWPSS based on AFBG**

MWPSS based on AFBG should be constructed on design and development of:

- theory and techniques of AFBGs that could simultaneously function as: a shaper of two-frequency probe radiation, a multiplexer, when the difference (address) frequency of the generated two-frequency radiations will be unique for each AFBG, and, finally, a sensitive element of MWPSS, so as the value of the difference (address) frequency is invariant to the applied physical fields;
- methods of the measurement information processing that will be transferred from the optical to the microwave frequency region, hence, the interrogation speed, resolution and measurement accuracy will be increased;
- AFBGs based joint field of multiplexed FOS for single-, few- and multi-sensor applications as the basis for the practical implementation of MWPSS, in which, especially in multi-sensor applications, are the questions of multiplexing and processing address information, not only in the presence of fluctuations and noise, but also in the presence of false addresses; measuring approaches for interrogation both point and quasi-distributed addressed FOSs and the principles of sensor networks building, especially when receiving measurement information from one AFBG at a time, but as response from several physical fields.

Consider the sets of analysis and synthesis problems that were solved in the development of the theory and technique of MWPSS based on AFBG.

The general abstract model of the functioning of a complex system when defining its inputs and outputs in system theory is considered as the ratio of the Cartesian product of a series of sets \( S \subseteq X \times Y \), where the set of inputs \( X = x_1 \times x_2 \times ... \times x_n \) consists of subsets \( x_i \); \( Y \) is the set of system outputs. If \( S \) is a function, then MWPSS based on AFBG is a functional system, which is a mapping of the abstract set \( X \) into the abstract set \( Y \), i.e. \( S : X \rightarrow Y \), which associates each element \( x \in X \) with a single element from \( Y \).

Substantiation of the MWPSS based on AFBG models corresponding to different levels of description, and the choice of initial sets defined by the above relation, should be carried out on the basis of problems solved by the system, taking into account the characteristic properties of the AFBGs, methods of their illumination and processing of reflected or emitted radiation from the gratings under conditions fluctuations and noise. The most consistent with modern concepts is the MWPSS based on AFBG model in the form of a space-time filter that allows controlling the parameters of physical fields.
contained in the amplitude, frequency, phase, and polarization parameters of the optical information field propagating in the fiber after interaction with the grating.

Obviously, the full abstract MWPSS based on AFBG model is complex, so using it even for analysis is fraught with serious difficulties. Therefore, the solution of the problems of analysis and synthesis of the MWPSS based on AFBG and the selection of appropriate strategies for their application should be made from the perspective of a systematic approach. The basis of the system approach is the description of the system in question at various levels of abstraction, so that the simplest description reflects the main aspects of the system’s behaviour. For the synthesis of the spatiotemporal structure of MWPSS based on AFBG, it is advisable to specify the general and particular models of their functioning. The general model should include particular models characterizing the basic functioning processes of the MWPSS based on AFBG.

3. Measuring level design for MWPSS based on AFBG

For MWPSS based on AFBG measuring level design we take the well-established notions of unified filtering microwave-photonic links of parallel (Figure 1) [11] and serial (Figure 2) types proposed in the works of the KNRTU-KAI scientific school [9, 10, 12, 13]. LD and modulators are the elements of probing and multiplexing radiation forming, optical filter is, as a rule, FBG sensor, and PD is element for conversion from optic to microwave range.

![Figure 1. Filtering microwave-photonic links of parallel type [11]:](image)

LD – laser diode, AM – amplitude modulator, PM – phase modulator, PD – photodiode

If we use these microwave-photonic links, we have to concern the generalized processor for microwave-photonic signal processing (Figure 3), also proposed in [11].

If we use AFBG, the processor has been developed that most closely meets the conditions for constructing MWPSS based on AFBG. The proposed scheme of the microwave photonic signal processor is shown in Figure 4.

It is clear that the TFORS, EOM, and TOF blocks are replaced by a single AFBG, which simultaneously functions as a tunable filter-former of probing radiation for an optical radiation source, an electro-optical modulator of the main tunable optical filter-sensor. OS is left to demonstrate the ability to connect an additional set of addressed FOS in an arbitrary serial, parallel, combined topology. Two types of PD are left for reception, both with a reference channel, and separately for each sensor. In addition, an optical filter with inclined linear characteristic is supplied between the sensors and PD to separate information for each measurement channel.
During the measurement process the location of AFBGs address components are changing their amplitude parameters, when central wavelength of gratings are changing. So, the parameters of beating signal between these components will be changing also.

**Figure 3.** Generalized processor for microwave-photonic signal processing:
TFORS – tunable filter of optical radiation source, EOM – electro-optical modulator (AM or PM), OS – optical splitter, TOF – tunable optical filter, DPD – differential photo detector, A – amplifier of RF signal

**Figure 4.** Generalized processor for signal processing in MWPSS based on AFBG

In classical measurement schemes, it is similar to Fabry-Perot scanning filters, diffraction grating, CCD-matrix, etc.

The proposed processor can be smart element of different MWPSS based on AFBG architecture covers the whole variety of applications in the field of sensor systems (general task) and each specific problem to be solved (particular tasks), as shown in the Table 1. The above examples indicate the possibility of using a unified concept for constructing MWPSS based on AFBG on the concepts of the microwave-photonic filtering links and processors with the simplest construction and low cost elements.

The performance indicators of the relevant parameters, such as probing rate, losses, resolution, and other indicators are very application specific. When using AFBG, it is sufficient to have a WLD operating in band of temperature measurement range (it is smaller in $N$ times versus MWPSS based on PFMS, where $N$ is number of FOSs), electro-optical modulators are excluded, and the FOSs with an unified optical Bragg wavelength are multiplexed and information processing is carried out at unique address frequencies in the RF range.

4. **Joint field of multiplexed FOS for MWPSS based on AFBG**

The decisive factor for the synthesis of MWPSS based on AFBG (taking into account the elimination of complex probing radiation sources and spectral methods for determining the central wavelength of FBG) is the set of parameters of the generated unified field of the addressed FOSs.

The state-of-the-art analysis of forming a joint field of the address less FOS [14,15], determining their response, quantity and topology, multiplexing options, allows us to represent the problem area of
forming a joint field of addressed FOSs based on AFBGs in the form of a multi-level hierarchical classifier (Figure 5).

**Table 1.** Processor elements using in different kind of MWPSS

| Kinds of MWPSS | Processor Elements |
|----------------|--------------------|
| Kind           | RF | LD | TFORS | EOM | OS | TOF | OC | PD | A | F | C |
| PFMS Analog    | LD, TLD, WLD       | +   | AM, PM | -   |   | FPC, IPC, DDL | -   | PD, DPD | ±   | ± | x |
| OEO Analog     | LD             | -   | AM, PM | ±   | IPC/DDL | ±   | PD | ±   | BP | = |
| PFP Analog     | LD             | -   | AM, PM, PolM | +   | IPC | +   | DPD | ±   | + | x |
| AFBG Analog    | WLD            | -   | -   | +   | IPC/IFLOF | +   | PD, DPD | ±   | SF | - |

**Note:** PFMS – photonic filter of microwave signal; OEO – optoelectronic oscillator; PFP – poly-harmonic frequency probing; TLD – tunable laser diode; WLD – wideband laser diode; PolM – polarization modulator; FPC – finite pulse characteristic; IPC – infinite pulse characteristic; DDL – discrete delay line; ILOF – inclined linear optical filter; BF – bandpass RF filter; SF – selective RF filter; «×» – electric commutator is in crossed position, «=» – electric commutator is in separate circuit, «+» – element is used, «-» – element is not used

**Figure 5.** Multi-level hierarchical classifier of the problem area of MWPSS based on AFBG design, manufacture and exploitation

The upper level of the classifier displays the AFBGs with the specified (input parameters) amplitude, frequency, phase, polarization and spatial characteristics of both the grating itself and the phase shifts.
that form the address and the corresponding transparency windows. That allows to implement the $N$-addressed joint field of FOS, which is used in various applications of MWPSS.

The number of required sensors $N$ is presented in the second level of the classifier.

The third level of the classifier corresponds to two main areas of interrogation of illuminating broadband laser radiation after its interaction with AFBG: reflectometric (reflection-based) and transmitted through the grating (propagation-based).

The fourth, fifth and sixth levels of the classifier present particular tasks, which are characterized by various sensor system topologies, spatial location, polarization features of both radiation and AFBG. For example, a single-, few-, and multi-sensor joint field with a series, parallel or combined connection of FOSs located in one or several separated measurement zones, with gratings recorded in ordinary single-mode, polarization-sensitive fibers or fibers that preserve polarization, etc.

The lowest level consists of independent, separate tasks, which are solved during the design, production, or exploitation processes of MWPSS based on AFBG in various applications $i = 1,\ldots$.

The given multi-level hierarchical classifier displays the problem area as a set of the existing theoretical and applied knowledge in the field of formation of a joint field of MWPSS based on AFBG. The solution of the general problem of the MWPSS based on AFBG development can be implemented according to the levels of the hierarchical classifier with the corresponding criteria for evaluating the effectiveness and optimization of the AFBS parameters for reflection-based and propagation-based sensors. The second to fifth classifier levels are characterized by the determination of the optimal AFBG parameters based on the results of mathematical modeling and experiments at the stage of creating MWPSS prototypes. At this stage, one can determine the frequency spacing and the amplitude of the address components, the spectral characteristics of the FBGs themselves, topologies and space-polarization parameters of their placement, calibration parameters.

At the same time, at lower levels, one can determine factors that allow determining the requirements for the structures that form the address when they overlap or are affected by physical fields that lead to the synthesis of false addresses or doubles, although they should be considered at higher levels of the classifier. In this case, it is required to solve complex equation sets, use special optical filters for frequency separation of FBG addresses, and create an effective system of post-detector filtering in the course of determining the measured parameters individually in each specific application. Examples include systems for the defense and fuel and energy industry, transport applications, medicine, which addresses issues of both few-sensor and multi-sensor applications [16–19].

Finally, the upper level is characterized by the improvement of metrological, technical and economic characteristics and the overall enhancement of the functional capabilities of the MWPSS based on AFBG. AFBG and methods of measurement data processing with the best properties should correspond to the extreme values of the mentioned indicators. To find the optimal solution, we will apply the criterion for the multifactorial nature of the problem developed in [16–18], MWPSS, which use the developed AFBG and information processing methods, must meet the requirements of universal standardized efficient multiplexing, which is ultimately achievable only in hybrid networks. In this regard, the process of their calibration is essential [20].

5. Conclusion

The concept of new class of sensor systems “MicroWave Photonic Sensor Systems based on Addressed Fiber Bragg Gratings” is presented. The sets of analysis and synthesis problems, measuring level design for point, few- and multi-sensor variants, and principle of joint field of multiplexed sensors construction for MWPSS based on AFBG are considered.

In the first AFBG version, it is necessary to form two symmetric discrete phase $\pi$-shifts in the FBG structure, which will determine the presence in the spectrum of two transparency windows and a unique frequency spacing between them. In the second version, it is necessary to form two identical ultranarrowband FBGs, also with a unique spacing between them. At the same time, this spacing ensures complete address of measurements, and processing of output signals in the region of the photodetector intrinsic noises minimum by evaluation of the envelope parameters of beating between the radiation
components of the FBG transparency windows or two FBGs at a unique and known address difference frequency, without the need to find the central wavelength of each AFBG. Thus, AFBGs become a multifunctional MWPSS element – a sensor, a dual-frequency optical radiation source for microwave processing of measurement information, and a multiplexer.

When implemented, the interrogation speed can be increased to hundreds of MHz, the resolution is up to units of Hz, which is determined by the parameters of microwave (not optical) processing, cost of system, its exploitation and design complexity are drastically decreased. Estimates show also that we can use a broadband laser source from optoelectronic interrogators, but with a smaller band, in the amount of the change in the central wavelength in the range of measurements of the physical parameter of one sensor, all sensors can have the same type of FBG with equal bandwidth and the same central wavelength, interferometer can consist only inclined linear optical filter and photodetector, which will ensure low cost MWPSS and compliance with the requirements of minimizing the types of FOS used in them.

Acknowledgments
The work was carried out with the financial support of the Ministry of Education and Science of the Russian Federation within the framework of the basic part of the Kazan National Research Technical University named after A.N. Tupolev-KAI state task 8.6872.2017/8.9 and within implementation of the federal special program “Research and development in the priority directions of development of scientific and technological complex of Russia for 2014–2020”, the agreement on granting a subsidy № 14.574.21.0188, unique identifier of applied scientific research (project) RFMEFI57418X0188.

References
[1] Wang C, Yao J P 2013 Optics express 19(21) 22868–22884 doi:10.1364/OE.21.022868
[2] Sun Q et al 2013 Proc. SPIE 9044 90440L doi:10.1117/12.2038040
[3] Djordjevic I B, Saleh A H, Küppers F 2014 Optics express 22(9) 10882–10897 doi:10.1364/OE22.010882
[4] Triana A, Pastor D 2017 Proc. SPIE 10231 102310L doi:10.1117/12.2267238
[5] Slepian D 1978 Bell System Technical Journal 57(5) 1371–1430 doi:10.1002/j.1538-7305.1978.tb02104.x
[6] Morozov O G, Aibatov D L, Il’in G I et al 2006 Proc. SPIE 6277 62770E doi:10.1117/12.692970
[7] Morozov O G, Natanson O G, Aybatov D L et al 2008 Proc. SPIE 7026 70260I doi:10.1117/12.801506
[8] Morozov O G, Natanson O G, Aybatov D L et al 2008 Proc. SPIE 7026 70260J doi:10.1117/12.801507
[9] Morozov O G, Aibatov D L 2007 Proc. SPIE 6605 660506 doi:10.1117/12.728450
[10] Il’In G I, Morozov O G, Il’In A G 2014 Proc. SPIE 9156 91560M doi:10.1117/12.2054753
[11] Morozov O G, Il’In G I, Morozov G A 2017 Systems of Signal Synchronization, Generating and Processing in Telecommunications (SINKHROINFO) 7997544 doi:10.1109/SINKHROINFO.2017.7997544
[12] Capmany J, Sales S, Gasulla I et al 2012 Waves 4 43–58
[13] Morozov O G, Morozov G A, Il’In G I et al 2015 Proc. SPIE 9533 95330Q doi:10.1117/12.2181435
[14] Khabibullin R A, Morozov O G, Sakhabutdinov A Z et al 2017 2017 Systems of Signal Synchronization, Generating and Processing in Telecommunications 7997568 doi:10.1109/SINKHROINFO.2017.7997568
[15] Pol’skiy E Morozov O G 1998 Proc. SPIE 3397 217–225 doi:10.1117/12.305056
[16] Morozov O G, Il’In G I, Pol’skiy Yu E et al 2012 Proc. SPIE 8410 84100Q doi:10.1117/12.923128
[17] Agliullin T A, Gubaidullin R R, Morozov O G et al 2019 Systems of Signals Generating and Processing in the Field of on Board Communications 8706815
doi:10.1109/SOSG.2019.8706815

[18] Maskevich K V, Mishakhov R Sh, Morozov O G et al 2019 Proc. SPIE 11146 111461R
doi:10.1117/12.2527561

[19] Vinoradov V Yu, Morozov O G, Anfinogentov V I et al 2019 Proc. SPIE 11146 111461K
doi:10.1117/12.2527564

[20] Sahabutdinov A Zh, Kuznetsov A A, Nureev I I et al 2015 International Journal of Applied Engineering Research 10(24) 44948–44957 doi: ijaer10/ijaerv10n24_163