УДК 621.317.799

Y.V. Shabatura, Cand.Tech.Sci., associate professor; O.V. Zelena

INFORMATION-MEASURING SYSTEM WITH TIME REPRESENTATION OF INFORMATION BASED ON FIBER-OPTICAL SENSORS

Expedience of fiber-optic IMS usage functioning on the basis of interval method of measurement is substantiated, realization of circular structure of IMS, using one communication line to which sensors, able to perceive code sampling signals for each separate sensor for fiber-optic IMS is considered. The given approach can be realized by means of spatial division of optic signals and transition from continuous to pulse operation mode.

Keywords: *fiber-optical technique, information-measuring system, interval method of measuring, circular structure spatial division of visual signals*

Introduction

Current situation in information-processing technologies development requires creation and elaboration of information measuring systems (IMS), which are based on new theoretical research [1,2]. Those research in their turn provide further development of such systems. Nowadays fiber-optic technologies development allows using its particular qualities and advantages not only in communication systems but also in IMS construction. Constantly increasing requests regarding reliability of different physical magnitudes measuring demand developing of new measuring methods and upgrading known ones. The leading specialists of the USA, Japan and Western Europe companies consider traditional electrical and electronic measuring systems to be replaced in the near future with fiber-optic measuring systems. Such optimistic forecast is based on several unique features of fibre-optic IMS (lack of influence of external electromagnetic interference on the results of measuring; high mechanical stability; safety and construction simplicity; signals transformation convenience and broad ability of matching with different electronic systems, etc.) [3,4].

Aim of research

To elaborate theoretical and practical aspects of construction of fiber-optic IMS with time representation of information.

Analysis of state-of-art of fiber-optic IMS

Almost all earlier developed IMS, based on of using optic fibres as a communication channels and sensors, had radial structure. The only differences were in using transition or strike types of sensors. Classical structure of such system is shown in Fig. 1.

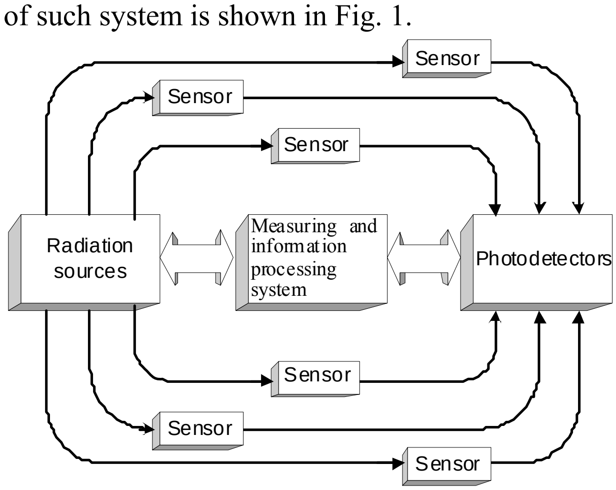

Fig. 1. Classical radial structure of fibre-optic IMS.

This structure along with all its advantages has also a number of disadvantages, and one of the most important of them is necessity to allocate physical communication channel for every separate sensor for every new measurement channel organisation [2]. At the same time we must note that the majority of modern electronic IMS use ring structure, where only one communication line with attached smart sensors is used. These smart sensors can perceive code selection signals for every separate sensor, whereupon the selected sensor is activated up and sends its measuring information to the communication channel.

The structure of such systems is unificated [2]. It foresees sequential transformation of measured information into the equivalent time slice together with following measuring time frame. It's easy to understand this transformation advisability, taking into consideration that time unit is the only SI unit (of 6) whose measuring ratio error today has reached the meaning of 10^{-15}. Unfortunately construction of fiber-optic IMS based on this principle is impossible nowadays because of absence of similar to electronic smart sensors fiber-optic ones [1]. But if at the heart of fiber-optic sensors function is placed the principle of time representation of information than becomes possible to create fiber-optic IMS with ring structure. At this structure separate fiber-optic sensors in series are linked by single fiber.

Problem set-up

Elaborate the structure and substantiate the expediency of usage of basically new kind of fiber-optic IMS, functioning on the basis of interval method of measuring [1].

Principle Statements

To implement the ring structure for fiber-optic IMS is possible only using interval method with optical signals space division and transition from continuous to pulse mode. In such system it's necessary to use transition sensors. Such system structure is shown in Fig. 2.

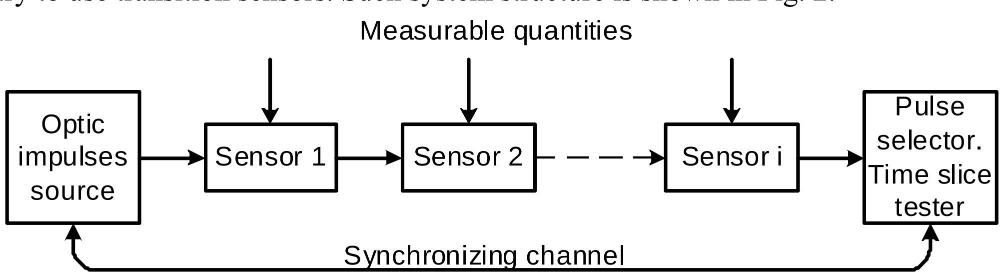

Fig.2. Fiber-optic IMS with ring structure

Sensors structure in presented system resembles Mach-Zehnder interferometers.

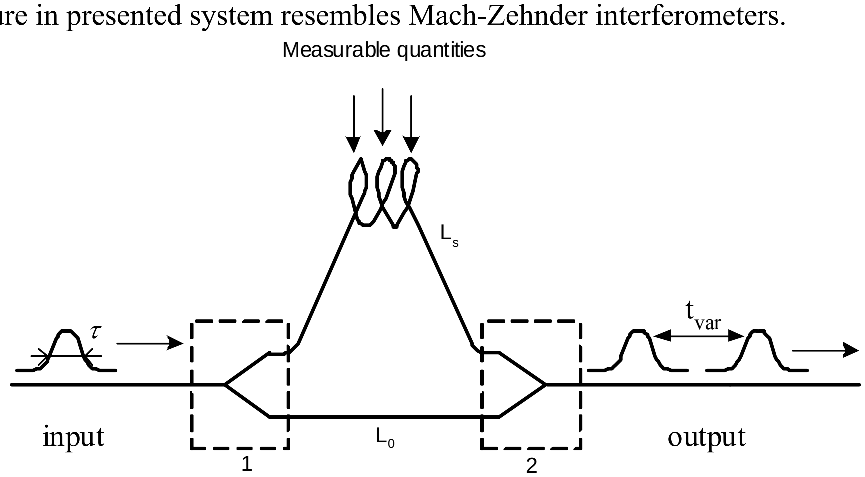

Fig.3. Structure of proposed fiber-optic sensors and principle of operation.

But, as it is seen from the Fig.3, interference phenomenon is not used here. Input optic pulse τ entering the first Y-like tap 1 is divided into 2 identical pulses. One of them goes through a short internal section of optic fiber L_0, and the other goes through a long sensor fiber lightguide section, which is directly influenced by measuring physical values. Relation of short section length L_0, sensor lightguide, pulse duration τ, and possible changes of pulse delay in sensor lightguide due to the impact of physical values and its dispersion are to be selected to avoid overlapping of both pulses in the second Y-like adder, as a result, their interference is missing.

Taking into account that pulse multiplication will be observed in the system while pulse propagation from the input to the first sensor and to the output of the last one, then for total amount of sensors in system n the number of optic pulses at the output will be:

$$N = 2^n \tag{1}$$

The length of fiber-optic lightguide short section L_0 is same in all the sensors, it can be found from the following relation:

$$L_0 = c \cdot t_0 \cdot n_0, \tag{2}$$

where: c - velocity of light propagation in vacuum; n_0 - fiber-optic lightguide core refractive index; t_0 - fiber-optic lightguide pulse delay time in fiber-optic lightguide.

The lengths of sensory fiber-optic lightguide sections are different in each sensor [6]. They can be determined by the formula:

$$L = c \cdot t_i \cdot n_i, \tag{3}$$

where: n_i – sensor fiber lightguide core refractive index in i-th sensor; t_i - delay time of optic pulse in sensor fiber lightguide of i-th sensor in the absence of measuring value influence.

Meaning of delay time in every sensor fiber lightguide is determined by the formula:

$$t_i = \Delta_i + t_0, \tag{4}$$

where: i - extra delay time in sensor fiber lightguide of i-th sensor.

It is chosen at the condition, that the impact of measuring value in preset measuring range will not lead to such change of that overlapping of optic pulses at the output of at least one sensor will become possible.

To formulate simple mathematical relations, which allow to calculate lengths of sensor lightguides, needed and sufficient to meet the requirements, formulated above, we will make the following assumptions. Let input optic pulse duration τ be equal 1 chosen time unit (t.un.). Delay time in short lightguide sensor t_0 also equals 1 t. un.

Measurable value influence on sensor lightguide doesn't cause delay time increase or decrease in this lightguide more than 1 t. un $(\Delta t < 1 t.un.)$. While performing these conditions additional delay time in sensor lightguide is determined by the formula:

$$\Delta_i = 2^i \text{ t.un.} \tag{5}$$

Full delay time:

$$t_i = 2^i + t_0, \tag{6}$$

where i – sensor number.

For the system with 3 measuring sensor, the information regarding the value of measured physical magnitudes for the first sensor fiber-optic lightguide will be determined by measuring time interval duration between the first and the second - T_{12}, or between III and IV - T_{34}, or between V and VI - T_{56}, or between VII and VIII - T_{78} output optic pulses in the order of their arrival from the output of the last measuring block [7, 8]. Accordingly the value of measured magnitude for the second sensor fiber-optic lightguide will be determined by measuring time interval between the first and the third T_{13}, or the second and the fourth T_{24}, or the fifth and the seventh T_{57}, or the sixth and the eighth T_{68} optic pulses. In the same manner the information regarding the value of measured magnitude will be found out for the third sensor fiber-optic lightguide.

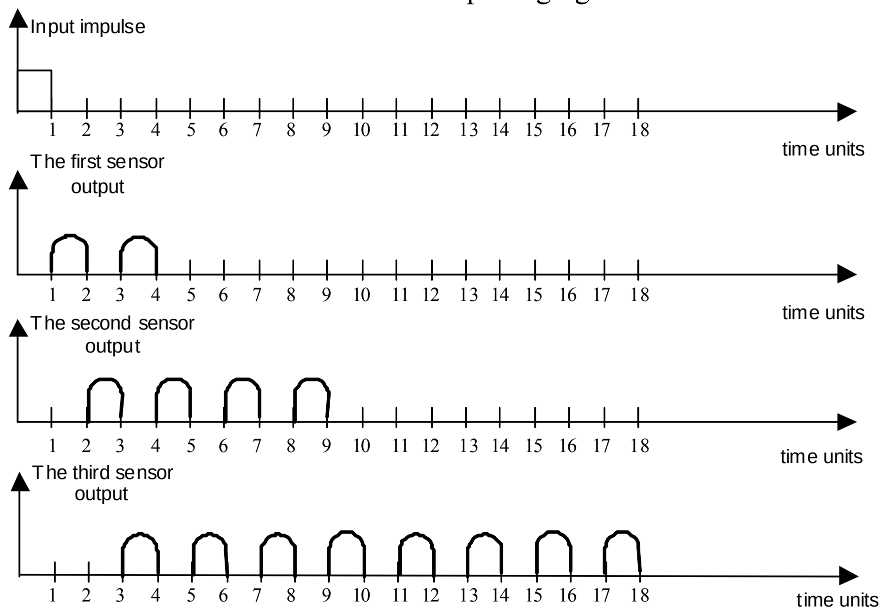

Fig.4. Pulse pattern.

In general, if duration of input pulse is τ, range of pulse delay time change in sensor lightguide, as a result of measurable value influence is Δt and delay time in short lightguide of the sensor is t_0, then calculated time delay in sensor lightguide is determined by the formula:

$$t_i = 2^{i-1} \cdot \tau + 2^{i-1} \cdot \Delta t + t_0 . \tag{7}$$

Thus calculated length of sensor lightguide of i-th sensor will be determined by the formula:

$$L_i = t_i \cdot n_i \cdot c , \tag{8}$$

where n_i - refractive index of sensor lightguide core in i-th sensor.

Let's examine some peculiarities of optic pulse time duration changes and its delay time in sensor lightguide, that may not be connected with the physical magnitude influence, so they have to be taken into account to provide necessary measuring accuracy.

As it is known, in case of multimode fiber usage, an optic pulse at its output will become wider than it was at its input. The widening of the pulse as a result of mode dispersion is due to different time of propagation in lightguide of the basic (fundamental) mode for which input angel of radiation relatively lightguide axis $q_z = 0$ hence propagation time is minimum:

$$t_{M.\min} = \frac{L}{c} n_1 , \tag{9}$$

where: L – lightguide length; n_1 – refractive index of lightguide core.

In case $q_z = q_c$ (q_c - angle that corresponds to full internal reflection between the core and light guide shell):

$$t_{M.\max} = \frac{L}{c}\left[\frac{n_1^{\;2}}{n_2}\right], \tag{10}$$

where: n_2 – refractive index of lightguide shell.

So pulse widening can be determined in the following way:

$$\Delta t_M = t_{M.\max} - t_{M.\min} = \frac{L}{c} n_1 \left[\frac{n_1}{n_2} - 1\right] \tag{11}$$

For approximate calculations it is expedient to apply the formula:

$$\Delta t_M = \frac{L n_1 q_c^{\;2}}{2c} \tag{12}$$

From previous relation:

$$L_M = \frac{2\Delta t_M c}{n_1 q_c^{\;2}} \tag{13}$$

Taking into account that $\Delta t_m = t_{\min}/2$:

$$L_M = \frac{t_{\min} c}{n_1 q_c^{\;2}} \tag{14}$$

Applying the obtained mathematical relations we can present the results of calculation for typical lightguides. For instance, if for optic delay line multimode lightguide with the following parameters is used: core diameter 50 micrometers, shell diameter 125 micrometers, aperture 0.2 and on wavelength 850 nm it has average bandwidth 1000 MHz at 1 kilometer, then, in such case on the level of 0.5 from the amplitude pulses will widen by 0.44 nsec/km and mean-square widening will be 0.187 nsec/kilometer. Thus to maintain distributive power at the level of not less than 1 ns, the length of the largest lightguide in delay line must not exceed 1.136 kilometers. Such value is more than sufficient for realization of information-measuring systems.

Using signal-mode lightguide, pulse widening occurs only due to chromatic dispersion, but its contribution into pulse widening is not important. For instance, it does not exceed 3.5 picoseconds in the range of wavelengths from 1285 to 1330 nm. It means that if the pulses with wavelength of 1325 nm are propagated in lightguide with zero chromatic dispersion on the wavelength of 1300 nm then complete root-mean square widening of pulse after 50 kilometers of routing across such like lightguide will be only 279 picoseconds.

For conventional materials, used in fiber-optic systems calculations were performed; the results of these calculations are presented in Table 1.

Table1

Material	Wave length in vacuum λ nm	Refractive index n	Wave length in material λ nm	Delay time		Linear length of material mm	
				1 ns	1 ps	For 1 ns	For 1 ps
Glass	850	1,4525	585,5	1	1	206.5	0.2065
Glass	1300	1,4469	898,5	1	1	207.3	0.2073
Glass	1550	1,4440	1073,4	1	1	207,7	0,2077
CaAlAs	850	3.6	236.1	1	1	83.3	0.083
Plastic	650	1,4 - 1,5	433 - 464	1	1	214,2	0,214
				1	1	200	0,200

In gradient fiber the core refractive index diminishes from the centre to periphery according to the quadratic law, that's why points, in which a ray changes its trajectory, move away from the axis as angle of propagation increases. Thus taking into account inverse dependence of light velocity on refraction index, we can see that those rays, which propagate closer to the axis, will have less velocity, and rays of modes of higher order will cover longer route, but still they will have higher propagation velocity, since they will pass through the section of lightguide core, which has less refraction index. Thus widening of optic pulse in gradient fiber will be smaller due to different mode speed and it can be determined by the formula:

$$\Delta\tau \approx \frac{n_1 L}{c} \cdot \frac{(n_1 - n_2)^2}{2n_2^2} \tag{15}$$

Unlike multimode fibers, in single-mode fibers time difference between modes extension is absent, that's why they are to be used in the suggested system. But when extending light pulse in any fibre, it's necessary taking into account group velocity dispersion and nonlinear nature of dependence of refractive index of intensity of pulse field.

In single-mode fibers for pulse propagation simulation process, the following equation can be used:

$$i\frac{\partial A(z,\eta)}{\partial z} = -\frac{k_L^*}{2}\frac{\partial^2 A(z,\eta)}{\partial \eta^2} + \chi |A(z,\eta)|^2 A(z,\eta), \tag{16}$$

where: $A(z,\eta)$ - function, which characterizes pulse field amplitude; z - coordinate; η - wave argument; k_L^* - group velocity dispersion coefficient; χ - coefficient, that takes into account pulse field influence on refractive index $\chi = k_L n_2^{\nabla} / n_0$, where n_2^{∇} - refractive index coefficient that depends on pulse intensity.

With the help of inverse dispersion method this equation was analytically solved for the fibre with positive group velocity dispersion and nonlinear refractive index [4].

In case if pulse passes through the fibre of sufficient length:

$$z \geq \frac{0{,}6\tau_{Lo}}{\sqrt{\chi k_L^* A_{o\max}}}, \tag{17}$$

its shape practically loses its dependence on initial shape and approaches to rectangular with duration:

$$\tau_{LT} = 2{,}9\sqrt{k_L^* \chi A_{o\max z}}, \tag{18}$$

and field strength of the pulse satisfies the correlation:

$$A_L \approx 0{,}6\sqrt{\frac{A_{o\max}\tau_{Lo}}{\sqrt{k_L^*\chi_z}}}\,. \tag{19}$$

For typical characteristics of single-mode fiber $n_2^{\nabla} \approx 1{,}5\cdot 10^{-22}\ M^2/B^2$, $\chi = 6{,}5\cdot 10^{-16}\ M/B^2$, $k_L^* \approx 6{,}5\cdot 10^{-26}\, C^2\cdot M^{-1}$. Output pulse extension will decrease with field strength growth of input pulse and will reach minimum value of pulse route length in linear environment:

$$z = 5{,}6\frac{\tau_{Lo}}{\sqrt{\chi k_L^*}A_{o\max}}\,. \tag{20}$$

Hence, if the examined characteristic of single-mode optic lightguides is used for construction of optic fibers based ring structure IMS, then the principal possibility of compensation of the error caused by dispersing pulse widening appears. So we can get informative signal caused only by those parameters, which are measured.

Conclusions

Thus, the structure of fiber-optic IMSs functioning on the base of interval measuring method was developed.

REFERENCES

1. Шабатура Ю.В. Основи теорії та практики інтервальних вимірювань. Монографія. – Вінниця: УНІВЕРСУМ-Вінниця, 2003. – 167 с.
2. Т. Окоси, К. Окамото и др. Волоконно-оптические датчики. – Л.: Энергоатомиздат, 1990. – 256 с.
3. Б.А. Красюк, О.Г. Семенов и др. Световодные датчики. – М.: Машиностроение, 1990. – 375 с.
4. А.Снайдер, Дж.Лав. Теория оптических волноводов. – М.: Радио и связь, 1987. – 525 с.
5. Херман И., Вильгельми Б. Лазеры сверхкоротких световых импульсов. – М.: Мир, 1986. – 368 с.
6. Vinarub E. I. Optical fibers make low-cost and reliable sensors//Electronic Design. – 1993. – # 7. – p. 188 – 195.
7. Verber S.M. The exiting promise of fiber-optical sensors//Mech. Eng. – 1998. – # 5. – p. 60 – 70.
8. H.F. Wolf Ed. Handbook of Fiber Optics: Theory and Applications – New York: Garland STPM Press, 1999. – 447 p.

Yury Vasil'ovich Shabatura – senior lecturer of the Department of metrology and industrial automatics;

Olga Viktorivna Zelena – student of group 1AM–03.
Vinnitsa National Technical University