NANOMATERIALS AND OPTOELECTRONICS IN HIGH-SPEED COMMUNICATION SYSTEMS

Zhuravleva, Lyubov M., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*
Malykh, Alexey N., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*
Malykh, Alexander N., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*

ABSTRACT

The article considers issues concerning increase in capacity of fiber-optic systems used on railways. The main directions of increasing information transmission speed are reviewed and analyzed, particularly enhancement of high-speed response of optical modulators and photodetectors through improving functional environment of optoelectronic devices and reducing inertia of the material. For this purpose, new materials are proposed in the form of multilayer nanostructures, along with manufacturing techniques and methods of assessing their quality characteristics required for design of new optoelectronic devices, that will positively affect railway communication systems' performance.

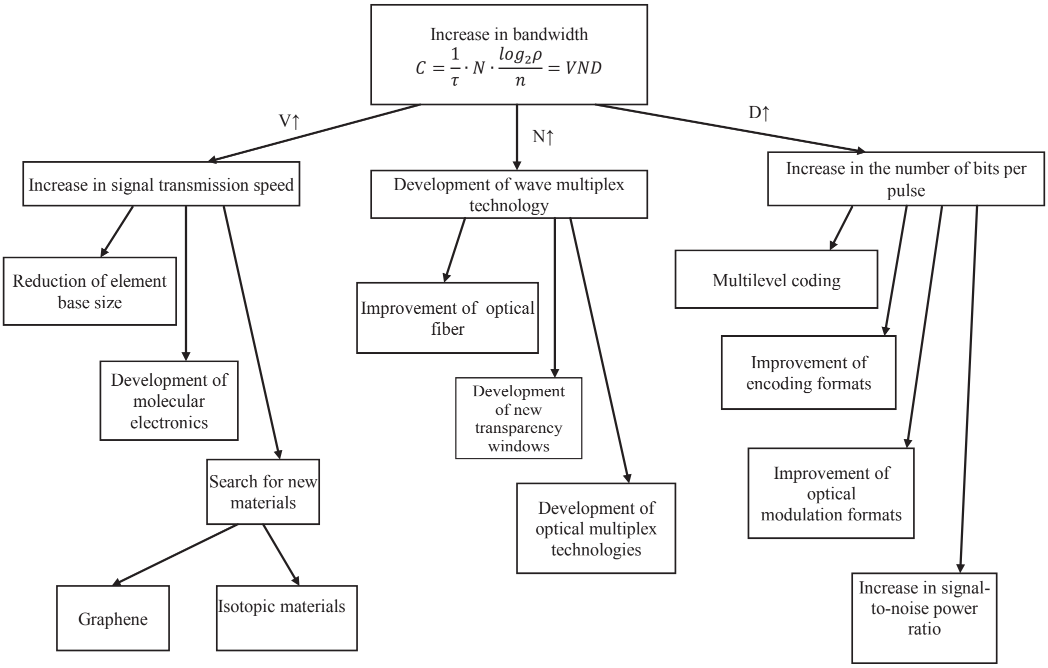
Keywords: *railways, communication channels, information network, isotope effect, bandwidth, nanostructure, fiber-optic system, optoelectronic devices.*

Background. *With constant growth in speeds and rail traffic volumes requirements for quality and speed of information transmission are also increasing. Therefore, a major objective is to create a high-speed communication system. Achieving that objective will improve efficiency of train control, will facilitate installing video surveillance at level crossings, tunnels and other critical facilities of railway transport. Currently, there is a steady increase in bandwidth of fiber-optic transmission systems (hereinafter – FOTS), at the end of the second decade of the century, it is expected to reach the value of petabit / s. Achievement of such a bandwidth will be possible by improving basic elements of FOTS, wave conductors, development of new optical ranges. Trends in this area are indicated in Pic. 1.*

Objective. *The objective of the authors is to forecast possible ways of enhancement of capacity of railway communication systems by using nanomaterials and optoelectronics, which can be applied in high-speed communication systems.*

Methods. *The authors use general scientific and radio engineering methods, simulation, comparative analysis, mathematical calculation.*

Results. *The first way is to increase signal transmission speed (expansion of opportunities of optoelectronic devices), the second is development of wave multiplex technologies (development of optical fiber frequency resource), the third is growth in the number of bits of information per one pulse. In the first case, the main role is played by a decrease in geometric dimensions and increase in quality of material of basic elements of FOTS, as well as of production technology. In the second we mean improvement of optical fiber, in the third case – development of information technology (compression*



Pic. 1. Ways to increase bandwidth of FOTS.

of signals, multilevel coding, improvement of optical modulation formats, reduction of quantization noise, etc.).

The increase in signal transmission speed has proved to be the most effective way to increase bandwidth, it depends on high-speed response of basic elements of FOTS, primarily optical modulators, photodetectors. Technical capabilities of FOTS are limited by capabilities of basic elements, they do not allow to increase information transmission speed up to 40 Gbit / s. However, optical fiber transmits signals with speed over 10 Tbit / c.

The speed increase can be achieved by reducing geometric dimensions, improvement of optoelectronic properties of materials and of manufacturing technology while transferring it into the field of nanotechnology. Existing physical and technological limits of reduction of the size of basic elements of FOTS suggest that in the future to promote high-speed response, a new generation of materials based on nanostructures of graphene and silicon, as well as innovative production technology are required. It is therefore necessary to develop a technique of designing new materials with nanostructures (functional media), providing the required high-speed response, and evaluation of optoelectronic parameters of updated element base.

The main characteristic of functional medium (base of modulators, photodetectors), which determines high-speed response of optoelectronic devices is inertia or duration of response of the material. This time can be represented as duration of buildup of the growth and rear fronts of the pulse t_{res} transporting in binary encoding one bit of information (Pic. 2).

The computational model of maximum permissible response time of the material to achieve the desired signal transmission speed can be represented as a formula for estimating Q-factor [1]:

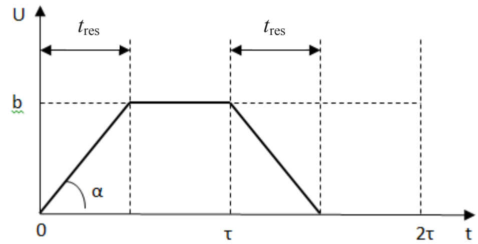
$$Q = \frac{\mu_1 - \mu_0}{2\sigma}, \qquad (1)$$

where μ_1 and μ_0 are values of signals (optical signal for modulator and electric signal for photodetector), corresponding to one and zero; σ is standard deviation of thermal noise of photodetector.

The values of μ_1 and μ_0 (1) can be found by calculating the square of pulse parts (Pic. 2). The result is the expression:

$$t_{res} = \tau\left(1 - \frac{2Q\sigma}{b}\right), \qquad (2)$$

where τ is duration of elementary pulse, or value reciprocal of signal transmission speed and frequency band f, GHz;



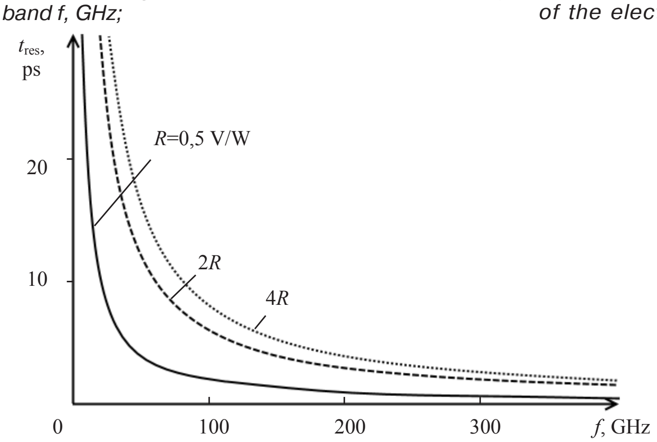
Pic. 2. Simplified model of momentum of pulse that carries one bit of information (t_{res} – response time of the material).

b is amplitude of electric pulse, which is equal to the product of optical pulse amplitude (A) and sensitivity of photodetector (R).

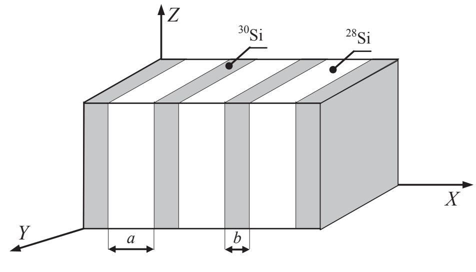
The minimal value of Q-factor in which probability of error value is 10^{-5}, and quality of communication quality becomes critical is Q = 4. Substituting in the formula (2) parameters of the photodetector (Σ, b) and the desired transmission speed ($1/\tau$), we can get estimation of time t_{res} of material, i.e., inertia, that the functional medium should have. The excess of this value will lead to the fact that the steepness of the pulse fronts will be insufficient to ensure the specified (minimum) quality of communication by photodetector. So, for the values A = 40 V, Σ = 2 mkV, R = 0,5 A / W, τ = 25 ps (40 Gb / s), value of t_{res} = 5 ps. Pic. 3 shows curve of dependence of response time t_{tr} on the set signal transmission speed for different values of sensitivity of photodetector.

As can be seen from Pic. 3, dependence is of linear (threshold) nature, which indicates that critical values of t_{res} exist, above which the inertia is not critical to increase signal transmission speed. Furthermore, requirements for quality of material of modulator or photodetector material for inertia are largely dependent on the design of the photodetector (values of thermal noise, quantum efficiency, sensitivity, etc.). Previously considered calculation model of inertia of material is suitable for evaluation of t_{tr} of modulator and photodetector.

It is known that optical modulators are distinguished by different operating principles. Therefore, precise figures of allowable inertia of the material can be obtained by analysis of the particular type of modulator. Thus, in Mach-Zehnder modulators, which are based on the phenomenon of electric deflection modulation, speed depends primarily on electronic polarization. It is determined by the value of dipole moment p, equal to the product of the electron charge on the shoulder. In bulk



Pic. 3. Dependence of response time of material on signal transmission speed.



Pic. 4. Superlattice model on silicon isotopes (a – quantum well, b – barrier).

materials, such as lithium niobate, the shoulder has an order of the lattice constant a_{lc}. In quantum structures (quantum wells) shoulder value is much higher (equal to the width of quantum well). The ratio of shoulders determines the degree of inertia of a material, change in the refraction coefficient and increase in modulation speed. In multilayer quantum structures, for example, in superlattices (Pic. 4) representing an alternation of layers of semiconductors with different band gaps, the shoulder is larger than in quantum wells.

In superlattices (hereinafter – SL) shoulder, depending on applied voltage, consists of one or several lattice spacings d (spacing is a sum of width of quantum well and the barrier width). Hence, the degree of growth of modulation frequency is equal to the ratio κ_d/a_{lc}, where κ_d is a number of spacings of SL that constitute the shoulder.

Isotopic superlattices are the most effective.

In such nanostructures spatial restriction of charge carriers is carried out via connection of layers of different isotopes of the same substance. Homojunctions obtained through this process will not cause mechanical stresses in the lattice constant either influence wave functions of free charge carriers. The possibility of obtaining isotopic nanostructures with the desired characteristics is based on changes in physical and technical parameters (band gap, refraction coefficient, electrical resistance, etc.) with various concentrations of isotopes of the same chemical element (isotope effect).

In the isotopic superlattices, where the depth of electrons penetration into neighboring quantum wells is larger due to lower height of potential barrier than in SL of different semiconductors, the shoulder can grow by several times, and the modulation frequency will increase by the order, which is well above 100 GHz [2].

Influence of isotopic superlattices (ISL) on operation of photodetectors (PD) is conditioned by a decrease in the number of channels of light dispersion due to uniformity of the lattice constant, and a significant reduction in defects. This affects the increase in quantum efficiency of the photodetector K_{ef}, which directly affects its sensitivity. To a large extent the sensitivity of the photodetector on isotopic superlattices increases through increasing the gain constant g. This occurs due to the rise time of the charge carriers h life in ISL and reduction of time of their transit t_{tst} through PD.

Thus, a twofold increase in speed of charge carriers in isotopically pure materials of silicon will increase lifetime of carriers and reduce their travel time along photodetectors [2]. Thus a gain constant and sensitivity will grow, and the power of thermal noise of the photodetector will decrease by 4 times. Furthermore, the use of silicon isotopic superlattices in semiconductor lasers improves efficiency of light sources by increasing «lifetime» of excitons. This reduces the emission band of semiconductor lasers by twice, reduces interchannel spacing, arranges additional wave channels in wave multiplex system of FOTS and improves spectral efficiency [3].

Conclusion. *Thus, bandwidth of FOTS with basic elements on isotopic superlattices increases by an order due to:*

1) increase in dynamic range of photodetector (four-fold increase in sensitivity and respectively four-fold reduction of noise power);

2) increase in modulation speed of optical modulators at least by two times;

3) reduction of emission band of semiconductor lasers by twice.

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Information about the authors:
Zhuravleva, Lyubov M. – Ph.D. (Eng.), associate professor of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, zhlubov@mail.ru.
Malykh, Alexey N. – 3rd year student of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, aleksey.malykh9@gmail.com.
Malykh, Alexander N. – 3rd year student of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, aleksandr_malykh@mail.ru.

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