Layered model for protecting speech information against leakage through an optoelectronic channel*

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Abstract

The article presents the results of a scientific and technical analysis and the development of a layered model for protecting speech information against leakage via an optoelectronic channel. It is determined that the primary factors influencing the effectiveness of protection against laser acoustic reconnaissance systems include not only the physical properties of materials but also their comprehensive multilayer arrangement. A model that describes the interaction of a laser beam with a multilayer structure (glass, films, coatings) and accounts for both forward propagation and the backscattered response is proposed. The model is formalized as a system of interrelated coefficients (K1–Kn) that represent the qualitative and quantitative composition of materials, properties of protective coatings, angle of incidence, and instrument technical specifications. The use of a "minimum-loss" principle is proposed for quantitatively assessing protection effectiveness. The study substantiates the feasibility of employing both aggregate and composite models to forecast the protective properties of window assemblies, thereby enabling the optimization of material selection and their combinations. It is shown that protection effectiveness depends on the damping characteristics of polymer films, the absence of resonance effects in insulated glazing units with panes of differing thicknesses, and the ability of smart glass to scatter laser radiation. The obtained results confirm the relevance of passive protection methods and provide a scientific basis for the development and implementation of high-technology solutions to ensure information security.

Keywords

speech information, optoelectronic channel of information leakage, laser acoustic reconnaissance systems, protective coatings, information protection, layered model

1. Introduction

The problem of unauthorized acquisition of confidential information is among the most pressing challenges in today's information environment. Technical channels of information leakage—particularly acoustic, vibroacoustic, and hybrid forms—are evolving alongside technological advances. The optoelectronic leakage channel that employs laser acoustic reconnaissance systems (LARS) poses a significant threat due to its high effectiveness, long operational range, and covert nature. Numerous methods for protecting information against leakage through various channels have been developed over recent decades. One of the key directions in ensuring information security is the detection and localization of potential technical channels of acoustic information leakage. In this field, a wide range of methods has been investigated, including both active and passive means of protecting speech information, leveraging specialized instruments, magnetostatics and electrostatics, and optical properties [1–7].

Among the most timely and promising directions in passive protection of speech information is the development of specialized coatings and films whose use can substantially reduce the risk of confidential information leakage by: absorbing or scattering the probing laser radiation; reducing the vibration amplitude of reflective surfaces, thereby hindering audio reconstruction; and deploying combinations of layered elements that yield a maximal degree of room protection.

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The protection level of premises against LARS-based interception of speech exhibits a complex dependence shaped by many interrelated quantities. Addressing this problem requires a comprehensive approach that accounts for material properties (glass, protective films), their multilayer combinations, and the interaction of the laser beam with surfaces. Developing a mathematical model that incorporates all these factors is critically important for creating effective solutions.

2. Theoretical Foundations of the Study

The operating principle of LARS is based on laser vibrometry methods. The system uses an invisible infrared (IR) laser beam for remote probing of a surface that vibrates under the action of an acoustic wave. A speech signal inside a room creates an acoustic field which, upon reaching the window glass, causes it to oscillate (vibrate). These oscillations modulate the reflected laser beam, converting acoustic information into an optical signal.

The key physical phenomenon used to read out this information is the Doppler effect. According to this effect, the frequency of light reflected from a moving object changes proportionally to the object's velocity. Because vibration is an oscillatory motion, it has a velocity that varies continuously. A laser beam reflected from a vibrating surface experiences a Doppler frequency shift. This shift is linearly dependent on the velocity of the glass's oscillation, enabling high-precision measurement of vibration parameters and reconstruction of the original acoustic signal.

The choice of the IR range for LARS is not arbitrary. It is dictated by the properties of the propagation medium—the atmosphere. Air exhibits so-called atmospheric transmission windows in the IR band (e.g., 3–4 μm and 8–12 μm), where atmospheric absorption is minimal. This allows the laser beam to maintain high power over substantial distances (300–1000 m), which is one of LARS's principal advantages. In addition, the invisibility of IR radiation to the unaided eye enhances the covert nature of reconnaissance. However, atmospheric conditions such as rain, fog, or snow can substantially attenuate the reflected signal through scattering, which is a key drawback of this channel.

The optoelectronic information leakage channel can be represented as a classical three-component system: "source of the hazardous signal—propagation medium—technical reconnaissance means." In this context:

- the source is the speech signal in the premises, which generates the acoustic field.
- the propagation medium is the air inside the room, which conveys the acoustic wave to the window glass.
- the reconnaissance means is the laser system that irradiates the vibrating surface and receives the modulated reflected signal.

The window glass plays an essential role in this chain. Under the influence of the acoustic field, it transforms from a passive barrier into an active source of vibrational motion, which becomes the carrier of the informative signal for LARS interception. Consequently, the effectiveness of room protection directly depends on the window system's ability to attenuate these vibrations and/or alter the characteristics of the reflected laser beam in a way that renders it unintelligible.

Prevention of information leakage through the acousto-optoelectronic channel can be achieved by:

- using vacuum and other protected window units, and frosting the exterior glass surface.
- applying vibrational noise masking to windows and other reflective objects.

Speech information protection is a set of measures aimed at preventing unauthorized access, use, dissemination, or alteration of speech data.

In studies [8–12], local researchers consider the protection of speech information from leakage through the optoelectronic channel. The proposed passive methods employing solar-control films do not deliver the desired anti-laser effect.

Copper-based films that protect windows against ultraviolet and visible infrared radiation, as described in [13], operate most effectively around 500 nm, which cannot provide the desired protection against laser probing because operational laser wavelengths are typically in the 650–3000 nm range.

Foreign authors in [14] analyzed options for reducing glass vibration and preventing laser eavesdropping, taking into account the influence of insulated glass unit design on LARS protective properties. The results show that only about 1% of the glass's vibrations are transmitted through the window frames, with the remainder concentrated in the glazing itself.

The effect of anti-laser aerosols on the intensity of acoustic signals is considered in [15]. It was found that the optimal signal strength corresponds to the amount of ablative material. This allows appropriate adjustment of laser focus during sampling to achieve optimal ablation based on the acoustic signal intensity.

For remote laser capture of voice, the backscattering characteristics of objects were analyzed in [16]. The results showed that the reconstructed speech amplitude gradually decreases as surface roughness increases. Moreover, the reconstructed acoustic signal amplitude increases with an increase in the metal's attenuation coefficient.

Based on photonic crystal superlattices and nanomaterials, multifrequency multilayer films and coatings have been developed [17]. These materials provide filtering of specific optical wavelengths while maintaining transparency across other parts of the spectrum.

Analysis of local and foreign research supports the conclusion that protecting speech data from potential leakage through technical channels is a critical task for ensuring information security in both governmental and business domains.

Any information leakage channel is formed from three components: a transmitter (source of the hazardous signal), a propagation medium for that signal, and a receiver (the information capture device). The optoelectronic channel is no exception. The hazardous signal in this case is the interlocutors' speech—i.e., sensitive information expressed aloud. The propagation medium for the hazardous signal, in our case, may include windows, paintings, mirrors, and other household objects located in the room. These structures exhibit membrane-like properties and are strongly affected by acoustic vibrations [10].

Thus, to exploit the optoelectronic information leakage channel, an adversary does not need to enter the premises; it is sufficient to gain access to adjacent buildings and install information-collection devices that convert structural vibrations within the controlled area into electrical signals.

Protection of speech information can proceed along two lines. First, protecting conversations that take place in enclosed rooms or within a controlled area. Second, protecting speech information within communication channels.

3. Problem statement

Existing architectural and construction solutions used in building or retrofitting premises do not always provide an adequate level of protection for speech information against laser acoustic reconnaissance systems (LARS). This is because LARS operation relies on remotely reading surface micro-vibrations (e.g., of window glass) induced by sound waves inside the room. Even minute vibrations can be converted back into intelligible speech using sensitive optical equipment.

Protection against LARS is an extremely complex, multifactorial task that depends on a large number of interrelated parameters. The challenge in countering LARS lies in the fact that window glass—typically perceived as a passive protective barrier—actually becomes an active element of the information-leakage channel. The security of a room depends on myriad interdependent factors, from the glass's chemical composition and geometric parameters to the type of protective coatings and environmental conditions. Therefore, the development of effective countermeasures requires a systematic approach that enables not only the identification but also the quantitative assessment of each factor's impact on the overall level of protection.

The absence of comprehensive, scientifically grounded models that account for combinations of layered elements and the bidirectional response to laser-beam propagation (into the premises and back) complicates the design of truly secure facilities. As a result, security measures are often inadequate, ineffective, or excessively costly without achieving the desired level of protection.

Thus, a current scientific and technical problem is the development and application of an effective model that permits quantitative assessment, forecasting, and minimization of the risks of speech information leakage through the optoelectronic channel from LARS, ensuring maximum protection of premises under contemporary information-security threat conditions.

Aim of the study: to advance and substantiate the proposed layered model for protecting speech information from LARS by detailing the physico-chemical and modeling factors that influence its effectiveness, and by formalizing these factors as predictive mathematical relationships.

4. Research Methodology

The methodology of this study relies on a comprehensive approach to examining the security parameters of the optoelectronic information-leakage channel, enabling investigation of the layer-by-layer interdependence and the influence of protective optical layers and the internal structure of glass on its protective characteristics against LARS. Specifically, based on assessments of the protection afforded by glass and film coatings against laser reconnaissance—carried out using X-ray fluorescence (XRF) and spectral analysis, as well as simplex-lattice (mixture) design in modeling glass characteristics—it can be generalized that the employed methods, the procedures developed from them, and the experimental investigations together constitute a methodology that fully accomplishes the stated objectives.

To construct a protective layered model of a multicomponent, architecturally configured structure for the optoelectronic information-leakage channel, we used results obtained in our prior studies.

In particular, we investigated the protective capability of glass against laser probing as a function of its elemental composition, including the influence of the elemental makeup of float glass on the reflectance and absorption coefficients of the probing radiation. Systematizing the elemental and quantitative composition of the studied window glass by periods and groups of the periodic table revealed a dependence between the electronic structure of the constituent chemical elements and the protective properties of the glass. The results showed that reflectance and absorption vary with changes in the glass's chemical composition, which makes it possible to predict properties and to design the glass composition with prescribed protective characteristics [18].

To ensure that all investigations were conducted correctly we created an experimental setting which helped us to receive precise numbers on protective capabilities of studied glass against laser probing (Figure 1). It includes: L—laser, —sample, D1 and D2—detectors (laser power measuring device).

Based on studying the reflectance of glass with a sputtered single-layer hafnium dioxide (HfO2) coating through its spectral characteristics, we proposed the use of protective films with high reflectivity that complicate or preclude optical interception. We substantiated the advantages of dielectric HfO2 films, since the reflectance of glass with such a deposited film is significantly higher compared to bare glass, which increases the glass's protective performance against speech information leakage by multiples. Moreover, the costs of producing and depositing such coatings are substantially lower than the costs of developing and manufacturing active countermeasures in the modern context, underscoring the advantages of passive methods for protecting speech information from optoelectronic readout [19].

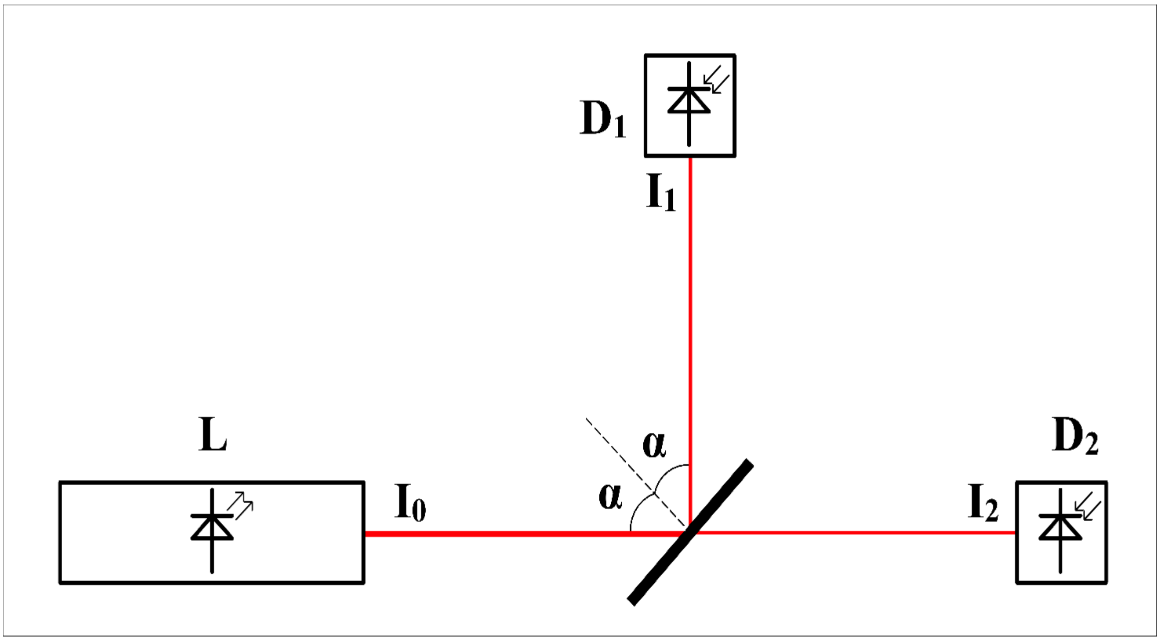

Figure 1: The scheme of an experimental setting for measuring protective capabilities of studied window glass

We also conducted studies and an effectiveness assessment of a protective semiconductor film, BaCuTeF, and proposed a method for obtaining an improved amorphous, electrically conductive protective film structure with subsequent crystallization through annealing in an argon atmosphere. Depending on the annealing temperature, this approach can significantly improve visible-light transmittance, increase the power of the reflected laser beam, and more strongly absorb laser radiation power compared with simple metallized films. This study led to the conclusion that installing such a protective film in combination with a high-reflectance dye layer on the exterior window glass of a building reduces or completely negates the effectiveness of laser interception of voice information, primarily due to the sharp drop in the power of the reflected or absorbed signal by the outer glass layer with the film coating [20].

Analyzing the results of the study describing the deposition methodology for a single-layer hafnium coating and the subsequent investigation of glass reflectance with the deposited film, together with [21], which examined the protective characteristics of textured films deposited on glass, we concluded that changing the tilt angle of the insulating glass unit and using textured films on the exterior side of the glass significantly influence the reflectance. This can provide effective protection against LARS at minimal cost.

Based on the analysis and synthesis of prior research results, it became possible to construct a comprehensive model of a multicomponent, architecturally configured structure for the optoelectronic information-leakage channel.

5. Results

The composite optoelectronic information leakage channel is formed by capturing information with an IR laser beam (LARS) from a flat glass surface vibrating under the influence of an acoustic wave carrying information. In the classical structure of an optoelectronic leakage channel, the sources of the acoustic signal in a room are, first and foremost, the person speaking and any reflected signal sources. In our case, window glass in a particular placement, of a specified chemical composition, and with various deposited layers and films, ceases to be only part of the propagation path and also acts as a source of vibrational oscillations. Depending on the number of protective layers on the glass, it can attenuate or, conversely, enhance the signal components available to LARS.

At the same time, based on experiments and studies [22], we note that vibration propagation differs depending on the configuration of barrier materials (glass and other enclosing structures) through which they propagate, as well as on the prior response to the scanning action of the laser beam.

Accordingly, we propose to represent the structure of the optoelectronic information leakage channel as a layered model (Figure 2).

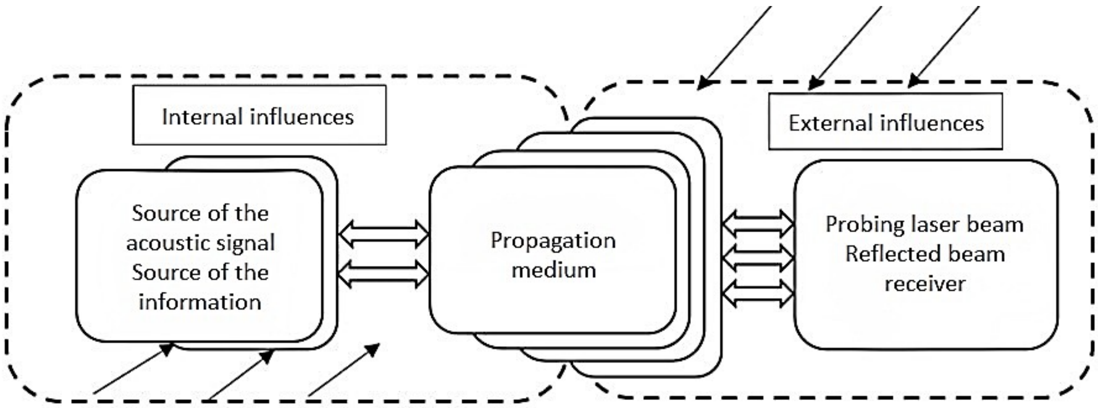

Figure 2: Protective layered model of a multicomponent, architecturally composed structure of the optoelectronic information leakage channel

Thus, the protection level of premises against speech interception by laser reconnaissance systems exhibits a complex dependence shaped by the configuration of many interrelated quantities [23]:

- K1: qualitative protection coefficient (elemental composition of the glass).
- K2: quantitative protection coefficient (stoichiometry of glass constituents).
- K3: protective coatings coefficient (films).
- K4: angular coefficient (tilt angle of the insulating glass unit).
- K5: angular coefficient (angle of incidence of the laser beam).
- K6: “sandwich” coefficient (arrangement/configuration of protective layers).
- K7: instrument technical characteristics coefficient.
- Kn: nth protection coefficient.

Coefficients K1 (qualitative, elemental composition) and K2 (quantitative, stoichiometry) are fundamental characteristics that determine the protective properties of glass. They influence both mechanical and optical parameters.

The glass composition directly affects its stiffness, described by Young’s modulus (E), which for silicate glass ranges from approximately 48 to 83 GPa. The higher the Young’s modulus, the smaller the amplitude of glass vibrations [24] under acoustic pressure. The introduction of oxides such as CaO, ZnO, Al_2O_3, and PbO can increase glass stiffness. Density also depends on composition; increasing the content of lead or barium oxides raises density, which in turn increases inertia and can affect the frequency response of vibrations.

Chemical composition and stoichiometry determine the glass’s absorption and transmission spectrum [25]. Even glass that is transparent in the visible band exhibits significant absorption in the IR region, which is critical for countering LARS. This absorption is due to various oxides and to hydroxyl (OH−) vibrational modes. For example, adding lead and barium oxides can increase transparency in the 2.5–4.5 μm range. Conversely, the formation of more ordered polycrystalline phases such as BaF_2 and Cu_xTe_{1-x} can reduce transparency due to increased absorption.

Thus, K1 and K2 establish the baseline physical parameters that serve as inputs for modeling glass vibrations induced by the acoustic signal and for modeling laser-beam attenuation.

Coefficients K3 (protective coatings) and K6 (the “sandwich” coefficient) describe how the glass’s baseline properties are modified by additional materials and constructions.

One of the most effective passive methods is laminated glass (triplex) [26], where two or more glass layers are bonded by a polymer interlayer, typically polyvinyl butyral (PVB). The key technical advantage is that the polymer acts as a damping layer, absorbing vibrational energy transferred from one glass ply to another and substantially reducing the overall vibration amplitude. This mechanism is fundamentally different from simple sound insulation and directly counters LARS-based interception. Damping effectiveness depends on the polymer’s acoustic properties, such as sound speed and absorption coefficient.

The “sandwich” coefficient (K6) further accounts for the layer combinations within the glazing unit. Robust protection is achieved by using panes of differing thicknesses (e.g., 6 and 8 mm), which helps avoid resonance effects that occur when panes share identical natural frequencies and can amplify vibration. Additionally, employing air gaps of different thicknesses improves sound insulation by promoting the scattering of sound waves.

A state-of-the-art solution is integrating PDLC (Polymer-Dispersed Liquid Crystal) films into insulating glass units. This “smart” glass can instantaneously switch from transparent to frosted under an applied electric field. In the frosted state, the liquid crystals are randomly oriented, producing strong light scattering. This effect can be leveraged against LARS, as it prevents acquisition of a well-defined reflected signal and complicates laser beam aiming.

Table 1 presents a comparative description of several protective materials for window systems.

Table 1
Comparative characteristics of protective coatings and materials

Material	LARS protection mechanism	Overall sound insulation (Rw/STC)	Optical properties	Additional advantages/ disadvantages
Ordinary glass	Low resistance to vibrations; partial absorption in the IR range	25–29 dB	High transparency in the visible range; low in the IR	Low cost; brittle; no protection
Triplex (Laminated glass)	Vibration damping due to a polymer interlayer	Up to 40 dB and higher	High transparency; filters up to 99% of UV radiation	High strength and safety (fragments do not scatter); more expensive
Insulating glass unit with panes of different thicknesses	Reduction of resonance, minimizing vibration amplitude	30–36 dB	High transparency	Increased overall thickness of the glazing unit
Smart glass	Scattering of the laser beam in the frosted state	Up to 35 dB	Switchable (controllable) transparency; blocks up to 98% of UV	Power-dependent; high cost; additional functions (can serve as a projection screen)

Coefficients K4, K5, and K7 describe not intrinsic material properties, but external factors and technical characteristics that influence the effectiveness of the leakage channel.

The angular coefficients K4 (tilt angle of the Insulating glass unit) and K5 (angle of incidence of the laser beam) are important for successful interception. When the laser beam strikes the glass at a non-normal angle, the reflected spot becomes elliptical. This spreads the beam energy over a larger area, which can reduce the intensity of the signal returned to the receiver.

Coefficient K7 accounts for the technical capabilities of the LARS apparatus, including laser power, photodetector sensitivity, and signal processing algorithms [9]. The effectiveness of any protection is evaluated not in absolute terms but relative to the adversary's reconnaissance capability. The main criterion is the signal-to-noise ratio (SNR) at the detector output. The goal of protective measures is to reduce this ratio to a level at which the informative signal becomes unintelligible.

The mathematical model describes minimizing information leakage through the optoelectronic channel against LARS, which corresponds to maximizing the room's protection. The total information loss consists of several components that are layered on the base material (glass). For each hypothetical layer there exists an optimal magnitude of risk reduction for LARS leakage that corresponds to a minimum. This minimum of losses correlates with a practical numerical characteristic $K^{\text{lars}}_{\min}$, which takes into account the composition and combination of layered elements involved in solving the room's security problem. In the general case, the final $K^{\text{lars}}_{\min}$ is composed of n protective layers, that is:

$$K^{\text{lars}}_{\min} = \sum_{i=1}^{n} K_n, \tag{1}$$

where $K^{\text{lars}}_{\min}$ is the coefficient of minimal loss of speech information, K_n is the minimal-loss coefficient contributed by the n-th protective layer.

We can posit that the layered model of the multicomponent, architecturally composed structure of the optoelectronic leakage channel unfolds at two levels: an aggregate model and a holistic (complex) model.

The aggregate model of a complex (layered) system consists of separate subsystems and a description of their interactions (in the classical manner). In this model, subsystems are represented by individual equations that relate outputs to inputs and subsystem parameters. In compact form:

$$\left\{\begin{matrix} K_1 & = & f_1(x_1, x_2, x_n...) \\ K_2 & = & f_2(x_1, x_2, x_n...) \\ K_n & = & f_n(x_1, x_2, x_n...) \end{matrix}\right\} \tag{2}$$

The interaction between subsystems (glass, deposited layers, protective films, arrangement, etc.) is such that the outputs of one subsystem serve as inputs to another and share the same identifiers in the aggregate model.

The complex (system-level) model views the source—propagation—receiver chain as a whole, without decomposing it into subsystems and internal processes. The overall protection coefficient can be expressed as:

$$K_{\text{prot}} = f K_n. \tag{3}$$

Moreover, for specific tasks the complex model can be obtained and represented as a consolidated aggregate model by reducing the system of equations to a single expression linking the system's inputs and outputs (through substitution), depending on the configuration of the elements used to protect against optoelectronic leakage.

This two-tier structure—aggregate and complex—is methodologically sound because it allows analysis both at the level of individual components (glass, films) and of the system as a whole.

However, to achieve scientific rigor, these models must be populated with concrete physical relationships.

The foundation for describing window vibrational behavior is the equation of forced oscillations. In the simplest case, the acoustic pressure acts as the external driving force, and the glass's elastic and damping properties are included:

The expression for the acoustic pressure force $F(t)$ can be written as:

$$F(t)=P(t)\cdot A, \tag{4}$$

where $P(t)$ is the acoustic pressure and A is the surface area.

Equation of motion with damping for an effective mass m:

$$m\frac{d^2x}{dt^2}+\beta\frac{dx}{dt}+kx=F(t), \tag{5}$$

where m is the effective mass of the glass, x is the displacement from equilibrium, β is the damping coefficient, k is the stiffness.

Coefficients K_1 and K_2 influence m and k, while K_3 and K_6 primarily affect β.

Modern methods such as the finite element method are used to model the complex vibrations of multilayer structures. The finite element method captures interlayer coupling between glass plies and polymer films, as well as the nonuniform spatial distribution of vibrations—effects that lie beyond simple analytical models. In this way, the complex model can be realized as a numerical simulation that integrates all coefficients into a unified system.

The terminal protection objective (K_{prot}) can be posed as minimizing the SNR at the photodetector input:

$$K_{prot}=min(SNR), \tag{6}$$

where SNR depends on the vibration amplitude, which in turn is a function of all coefficients $K_1 \ldots K_n$.

The advantage of these approaches is that, depending on the system's objectives and component specifications, one can flexibly compose the overall behavior from modular elements with known parameters or criteria, even without delving into internal structure, focusing solely on the required outcome. Evidently, the proposed model enables both approaches: experimental studies of individual layers and forecasting the theoretical capabilities of an integrated protection system for speech information against LARS.

6. Conclusions

As a result of this study, we have constructed a protective model for a multicomponent, architecturally composed structure of the optoelectronic information leakage channel. The model accounts for combinations of layered elements, the forward and backward response of a laser beam propagating into and out of the premises, and is formulated at both aggregate and complex levels.

It has been established that the protection of premises against LARS-based interception of speech is not a linear function; rather, it is shaped by a complex combination of interrelated parameters, including the bidirectional response of the laser beam as it traverses multilayer elements of building structures (e.g., glass, protective films, and coatings).

The developed mathematical model, which describes the minimization of information losses through the optoelectronic channel under LARS probing, makes it possible to determine the optimal reduction of risk for each hypothetical layer of the base material. This, in turn, corresponds to the maximum achievable level of premises protection.

The "minimum-loss" concept reflects a practical numerical measure of the effectiveness of specific combinations of layered elements that form the room's security system. Accordingly, the study provides a scientific foundation for the design and optimization of protective systems, enabling the most effective countermeasures against laser acoustic reconnaissance through targeted manipulation of the physical properties of multilayer architectural components.

The conducted scientific and technical analysis confirms the high relevance of protection against the optoelectronic leakage channel and substantiates the systems approach proposed in the layered model. The research offers concrete justification for each protection coefficient (K1–Kn), linking them to material properties such as Young's modulus, absorption spectra, and damping characteristics.

It is shown that effective protection requires a comprehensive approach that combines passive methods aimed at attenuating structural vibrations and the laser beam with active systems that introduce interference. Despite its high effectiveness and stealth, the optoelectronic channel exhibits vulnerabilities stemming from its dependence on material properties and atmospheric conditions.

Development of the mathematical model using the equations of forced oscillations and numerical techniques such as the finite element method enables a transition from theoretical assumptions to precise calculations. This opens the way to high-technology solutions—including smart glass and laser interference systems—that can ensure robust protection of confidential speech information under contemporary conditions.

Declaration on Generative AI

While preparing this work, the authors used the AI programs Grammarly Pro to correct text grammar and Strike Plagiarism to search for possible plagiarism. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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