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A. Kokhanov, DSc., Prof.,
I. Prokopovych, DSc., Prof.,
T. Sikach
Odessa Polytechnic National University, 1 Shevchenko Ave., Odesa, Ukraine, 65044; e-mail: t.s.sikach@op.edu.ua

HYBRID INTELLIGENT ADAPTIVE FIBER SYSTEM FOR REDUCING NONLINEAR EFFECTS IN WDM SYSTEMS WITH METROLOGICAL ASPECTS

О. Коханов, І. Прокопович, Т. Сікач. **Гібридна система інтелектуального адаптивного оптоволокна для зменшення нелінійних ефектів у системах WDM з метрологічними аспектами.** Нелінійні оптичні ефекти, зокрема самофазова модуляція (SPM), перехресна фазова модуляція (XPM) та чотирихвильове змішування (FWM), суттєво обмежують продуктивність сучасних оптоволоконних систем з мультиплексуванням за довжиною хвилі (WDM), що призводить до деградації якості сигналу, зростання показника бітової помилки (BER) та скорочення максимальної дальності передачі. Для подолання цих обмежень у статті запропоновано інноваційну гібридну інтелектуальну адаптивну оптоволоконну систему (IAF), яка поєднує електрооптичне та акустооптичне керування показником заломлення в фотонно-кристалічних волокнах з рідкими кристалами (LC-PCF). Використання прозорих індій-тін-оксидних (ITO) електродів та п'єзотрансд'юсерів дозволяє забезпечити високу точність і швидкість динамічної модуляції нелінійного коефіцієнта n^2 та ефективної площі моди A_{eff}. Це дає змогу в реальному часі адаптувати оптичні властивості середовища, мінімізуючи нелінійні спотворення і покращуючи якість передачі. Ключовим елементом системи є інтеграція сучасних методів штучного інтелекту, зокрема глибоких нейронних мереж (DNN) та алгоритмів посиленого навчання (RL), які здійснюють оптимізацію параметрів управління на основі безперервного моніторингу сигналу. Таке інтелектуальне керування дозволяє враховувати мінливі умови експлуатації, виявляти та коригувати нелінійні ефекти з високою точністю. Особливу увагу приділено метрологічним аспектам системи: розроблено комплексні методи калібрування сенсорів і оцінки похибок, що забезпечують достовірність і стабільність вимірювань. Завдяки цьому підвищується надійність адаптивної системи, а також її здатність підтримувати оптимальні параметри протягом тривалого часу. Результати чисельного моделювання демонструють значне покращення параметрів системи: зниження нелінійного коефіцієнта γ на 25…50%, зменшення BER на 20…35% та збільшення максимальної дальності передачі на 15…25% у високошвидкісних WDM системах із пропускною здатністю 400G та 800G. Запропонована гібридна інтелектуальна адаптивна система має великий потенціал для застосування у магістральних, підводних і довготривалих оптоволоконних мережах, забезпечуючи підвищену ефективність, надійність та адаптивність сучасних телекомунікаційних інфраструктур.
Ключові слова: оптоволокно, нелінійні ефекти, електрооптичний ефект, акустооптичний ефект, штучний інтелект, метрологія, WDM

A. Kokhanov, I. Prokopovych, T. Sikach. **Hybrid intelligent adaptive fiber system for reducing nonlinear effects in WDM systems with metrological aspects.** Nonlinear optical effects, including self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), significantly limit the performance of modern wavelength-division multiplexing (WDM) fiber-optic systems, leading to signal quality degradation, increased bit error rate (BER), and reduced maximum transmission distance. To overcome these limitations, this paper proposes an innovative hybrid intelligent adaptive fiber-optic system (IAF) that combines electro-optic and acousto-optic control of the refractive index in liquid crystal photonic crystal fibers (LC-PCF). The use of transparent indium-tin-oxide (ITO) electrodes and piezoelectric transducers enables precise and rapid dynamic modulation of the nonlinear coefficient n^2 and effective mode area A_{eff}. This allows real-time adaptation of the optical properties of the medium, minimizing nonlinear distortions and enhancing transmission quality. A key element of the system is the integration of advanced artificial intelligence methods, specifically deep neural networks (DNN) and reinforcement learning (RL) algorithms, which optimize control parameters based on continuous signal monitoring. Such intelligent control accounts for variable operating conditions, accurately detecting and compensating nonlinear effects. Particular attention is given to metrological aspects: comprehensive sensor calibration methods and error assessment techniques have been developed to ensure measurement reliability and stability. This increases system robustness and its ability to maintain optimal parameters over extended periods. Numerical simulation results demonstrate significant system performance improvements: a reduction in the nonlinear coefficient γ by 25…50%, a decrease in BER by 20…35%, and an increase in maximum transmission distance by 15…25% in high-speed 400G and 800G WDM systems. The proposed hybrid intelligent adaptive system shows great potential for deployment in backbone, submarine, and long-haul fiber-optic networks, enhancing efficiency, reliability, and adaptability of modern telecommunication infrastructures.
Keywords: optical fiber, nonlinear effects, electro-optic effect, acousto-optic effect, artificial intelligence, metrology, WDM

1. Introduction

Fiber-optic systems form the backbone of modern telecommunications, but nonlinear effects (SPM, XPM, FWM, SRS, SBS) limit their bandwidth and transmission distance. Nonlinearity arises (1) due to the dependence of the refractive index on light intensity:

$$n = n^0 + n^2 I , \tag{1}$$

where: n^0 is the linear refractive index, n^2 is the nonlinear refractive index, and $I = |E|^2$ is the intensi-

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ty. The nonlinear parameter – coefficient γ in an optical fiber (2):

$$\gamma = \frac{2\pi n^2}{\lambda A_{\text{eff}}}, \tag{2}$$

where: λ is the wavelength, and A_{eff} is the effective core area. The article proposes a hybrid IAF (Intelligent Adaptive Fiber) system that combines electro-optic (1…10 ns) and acousto-optic (1…10 μs) control with AI for adaptive modulation of n^2 and A_{eff}.

2. Literature Review and Problem Statement

2.1. Nonlinear Effects

Signal propagation in fiber-optic media is described by the Nonlinear Schrödinger Equation (NLSE) (3), which accounts for dispersion, losses, and nonlinearity. Nonlinear effects arise from intense light fields that alter the local refractive index of the fiber, leading to phase and spectral distortions. Self-Phase Modulation (SPM) changes the signal phase due to its own intensity, affecting the pulse spectrum width [1]. Cross-Phase Modulation (XPM) causes mutual interference between channels in WDM systems, resulting in phase distortions. Four-Wave Mixing (FWM) generates new frequencies due to the interaction of three or more waves, leading to channel crosstalk [2]. Accurate assessment of nonlinear effects involves optical spectrum analysis and Q-factor measurements. Controlling the nonlinearity parameter (γ) requires precise measurement of the refractive index and mode field area, achieved using calibrated interferometers and OTDR. Modeling of effects accounts for intensity measurement errors of up to 0.3 dB. Errors in spectrum measurements can lead to incorrect compensation parameter calculations. Metrological models establish statistical reliability bounds for system operation:

$$\frac{\partial A}{\partial z} + \beta^{(1)} \frac{\partial A}{\partial t} + i \frac{\beta^{(2)}}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\alpha}{2} A = i\gamma |A|^2 A, \tag{3}$$

where: A is the amplitude, β^1, β^2 are dispersion parameters, and α is the loss coefficient, i indicates that this term affects the phase and shape of the pulse in the frequency domain and means that the signal phase changes proportionally to its power.

Main effects (Fig. 1.): SPM: Phase change due to the signal's own intensity; XPM: Interaction between WDM channels; FWM: Generation of new frequencies.

2.2. Electro-Optic Control

The electro-optic effect (Pockels effect) (4) allows modulation of the material's refractive index under an external electric field. The refractive index change is proportional to the electric field strength and the electro-optic coefficient of the material (e.g., r^{33} for lithium niobate or LC). This enables dynamic modulation of n^2 on nanosecond timescales, allowing rapid adaptation of fiber parameters to changes in traffic or external conditions in real time. Transparent oxide electrodes (ITO) enable integration into photonic architectures without significant losses:

$$\Delta n_{\text{EO}} = \frac{r^{33} n_0^3 E}{2}, \tag{4}$$

where: $r_{33} \approx \frac{30...100}{V}$ pm/V; E is the electric field.

Response time: 1…10 ns. The refractive index change is measured using interferometric schemes with an accuracy of 10^{-4}. Voltage source stability is controlled via a metrological module with calibration of ±0.1 V. The effect of noise on electrode voltage is analyzed using harmonic analysis with modulation. The error in determining Δn_{EO} is accounted for in the γ model, enabling the system to respond to input signal changes with 0.5% accuracy in real time.

The electro-optic control model involves altering the refractive index of the fiber core material (Fig. 2) using an applied electric field, achieved through piezoelectric or electro-optic effects (Kerr, Pockels, etc.). The model includes:

– Optical fiber with core and cladding;
– Electrodes placed on the fiber sides to apply the electric field;
– Electric field source (voltage);
– Refractive index change in the fiber core due to the electric field;

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– Input and output optical signals passing through the fiber.

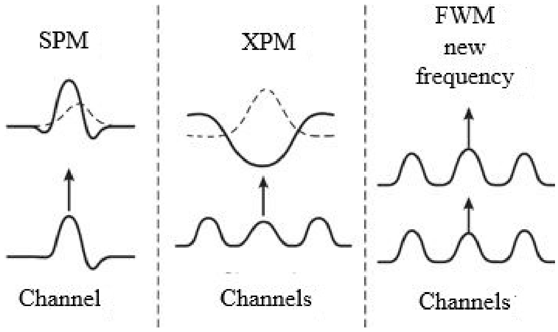

Fig. 1. Schematic representation of SPM, XPM, and FWM in a WDM system

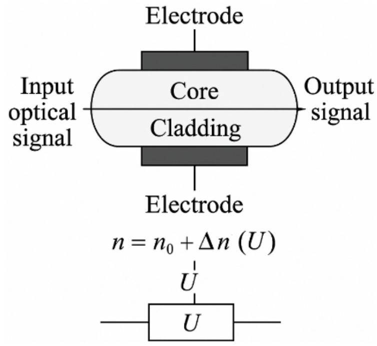

Fig. 2. Model of electro-optic refractive index control in an optical fiber

2.3. Acousto-Optic Control

Acousto-optic control relies on modulating the refractive index via acoustic waves, which create periodic density changes in the material (5). This acts as a diffraction grating, altering the effective mode area (A_{eff}) indirectly controlling γ. Acoustic wave control is achieved using piezoelectric transducers generating waves up to 100 MHz. Compared to electro-optic control, this method is slower but offers greater modulation depth. Systems combining EO and AO effects can dynamically adjust the optical field geometry:

$$\Delta n_{\text{AO}} = \frac{p \cdot \rho^0 \cdot v^2}{2n^0 \cdot \cos(k_a z - \omega_a t)} I\alpha \ < \ 0.2\,, \tag{5}$$

where: $p \approx 0.2$; ρ_0 is the density; $v \approx 5.9$ km/s .

Laser Doppler interferometers are used to determine the acoustic wave profile with 1 µs accuracy. AO (Fig. 3) effect parameters are incorporated into the fiber control model, with errors added to the γ uncertainty. Acoustic wave measurement standards ensure inter-laboratory reproducibility. PZT transducer stability is maintained via thermal stabilization with ±0.1 °C accuracy. The total metrological error in A_{eff} modulation is ≤0.7%.

This diagram illustrates the working principle of an acousto-optic modulator (AOM) (Fig. 4) integrated into a fiber optic system. Here’s a breakdown of each labeled component:

1. Input Fiber. Delivers the incoming optical signal to the modulator.

2. Acousto-Optic Modulator (AOM). A device that uses sound waves (acoustic waves) to modulate the properties of light (such as its intensity, frequency, or direction). Light enters from the input fiber, interacts with the acoustic waves in the modulator, and exits via the output fiber.

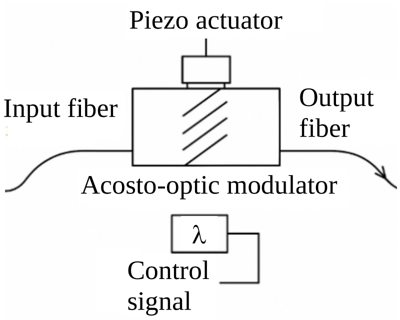

Fig. 3. Structure of an AO modulator in a fiber-optic system

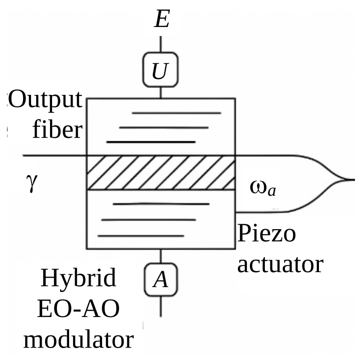

Fig. 4. Diagram of the hybrid EO-AO modulator for controlling γ

3. Piezo Actuator. Generates acoustic waves within the modulator when driven by a control signal. Works based on the piezoelectric effect-converts electrical signals into mechanical vibrations (sound waves).

4. Control Signal (λ). The electrical input that controls the piezo actuator. Determines the modulation characteristics such as frequency and amplitude of the acoustic wave.

5. Output Fiber. Carries the modulated optical signal out of the AOM for further transmission or processing.

A control signal drives the piezo actuator, which creates acoustic waves in the AOM. These waves modulate the optical signal passing through the input fiber. The modulated signal then exits via the output fiber. This setup is common in laser modulation, signal processing, and optical switching applications.

2.4. Hybrid Model

The hybrid model combines electro-optic and acousto-optic modulation (6) to control n^2 and A_{eff} simultaneously, enabling precise tuning of γ based on load or signal quality conditions. The effective refractive index formula incorporates both effects, providing an extended control space. This allows the system to respond to non-stationary effects, such as rapid traffic or spectral changes (7). AI algorithms optimize the combination of E and ω_a to minimize γ:

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$$n_{\text{eff}} = n^0 + \Delta n_{\text{EO}} = \Delta n_{\text{AO}} E, \tag{6}$$

$$\gamma = \frac{2\pi(n^2 + \Delta n_{\text{EO}} + \Delta n_{\text{AO}})}{\lambda A_{\text{eff}}}. \tag{7}$$

AI optimizes E and ω_a to minimize γ.

Each contribution to $n_{\text{eff}}(\text{EO, AO})$ is measured separately, accounting for interference effects. Metrological integration of both mechanisms requires synchronized calibration using laser trackers and phase shift recorders. A quadrature summation method accounts for total error, enabling reliability prediction across operating modes. Measurement units must be certified per ISO/IEC 17025 [3, 4].

The hybrid electro-optic (EO) and acousto-optic (AO) modulator (Fig. 4) used for dynamic control of light propagation through an optical fiber. This hybrid EO-AO modulator allows simultaneous electrical and acoustic control of the refractive index n_{eff}, enabling fine-tuned modulation of the light signal within an optical fiber. The electric field (E) modifies the material through the electro-optic effect, while the acoustic wave (ω_a) generated by the piezoelectric transducer enables acousto-optic interaction. The combined effects influence the modulation parameter γ, which is essential for high-speed or adaptive photonic systems.

2.5. Metrological Aspects

Metrology in systems controlling n^2 and A_{eff} is critical, as small measurement errors can significantly impact BER and γ. To evaluate the impact of variations in the electric field E and intensity I, the following model is used (8):

$$\delta n^2 = \sqrt{\left(\frac{\partial n^2}{\partial E}\cdot \delta E\right)^2 + \left(\frac{\partial n^2}{\partial I}\cdot \delta I\right)^2}. \tag{8}$$

Signal intensity is monitored using spectrometers with 0.01 nm resolution. OTDR and reference fiber calibration systems achieve <0.5% accuracy for n^2. The error in γ (9) accounts for uncertainties in E, ω_a and intensity, ensuring system operation within acceptable standards. Sensitivity S (10), which determines how changes in $n^2 \gamma$, must be precisely known for each transmission session:

$$\delta_\gamma = \left|\frac{2\pi}{\lambda A_{\text{eff}}}\right| \delta n^2 + \left|\frac{2\pi n^2}{\lambda A_{\text{eff}}^2}\right| \delta A_{\text{eff}}, \tag{9}$$

$$S = \frac{\partial \gamma}{\partial n^2} = \frac{2\pi}{\lambda \cdot A_{\text{eff}}}. \tag{10}$$

The system must have traceable uncertainty sources linked to international standards. Metrological certification occurs at least annually, with results recorded in digitally signed logs. All sensors are verified per national metrological requirements. Comprehensive uncertainty evaluation predicts the maximum transmission accuracy for each WDM channel [4].

3. Purpose and objectives of the study

3.1. Purpose and Objectives of the Research on a Hybrid Intelligent System for Nonlinearity Control in Optical WDM Networks

The primary objective of this research is to design, model, and analyze a hybrid intelligent adaptive fiber-optic system (IAF) that integrates electro-optic (EO) and acousto-optic (AO) modulation

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techniques within a liquid-crystal photonic crystal fiber (LC-PCF) architecture. This system aims to provide real-time, dynamic control over the nonlinear optical parameters, such as the nonlinear refractive index n^2 and the effective mode area A_{eff}, by leveraging the unique tunable properties of liquid-crystal materials and the structural dispersion-engineering capabilities of photonic crystal fibers. The hybrid EO–AO approach enables simultaneous electrical and acoustic tuning, allowing precise modulation of both phase and amplitude characteristics of optical signals as they propagate through the fiber. The electro-optic effect-realized through transparent ITO electrodes-provides fast and localized index control, while the acousto-optic modulation-implemented via PZT piezotransducers-enables mechanical deformation and adaptive mode-field shaping, further influencing nonlinear behavior. To enhance system performance and adaptability under real-world, time-varying conditions, the architecture incorporates AI-driven control mechanisms, including deep neural networks (DNN) for signal pattern recognition and reinforcement learning (RL) algorithms for adaptive optimization of control parameters (electric field strength E, acoustic frequency ω_a, and signal intensity I) [6]. These algorithms continuously monitor signal quality metrics such as bit error rate (BER) and spectral characteristics, dynamically adjusting system parameters to suppress nonlinear distortions like self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). Ultimately, this research aims to create a robust and intelligent platform for next-generation WDM fiber-optic communication systems, capable of extending transmission distance, reducing error rates, and adapting to high-capacity networks (400G/800G and beyond) with high levels of precision, reliability, and spectral efficiency [6, 7].

Develop a model of a hybrid EO-AO modulator, considering the influence of electric fields and acoustic waves on the refractive index and effective mode area in LC-PCF.

Investigate the impact of the fiber's structural components, including [8, 9]:

– LC core with a diameter of 8…10 μm;

– Transparent ITO electrodes (100 nm);

– PZT-based piezotransducers (50…100 μm);

– Silica cladding with low attenuation ($\alpha < 0.2$ dB/km), on nonlinearity, dispersion, and system stability.

Evaluate the metrological aspects of system performance, including:

– Accuracy of $n^2$and A_{eff} measurements;

– Influence of errors in E, ω_a, and I on the nonlinear coefficient γ;

– Use of spectrometers, OTDR calibration, and sensor verification in accordance with ISO/IEC 17025 standards.

Integrate AI-based algorithms, including:

– Deep neural networks (DNN);

– Reinforcement learning (RL), for real-time monitoring and optimization of control parameters.

Perform numerical modeling of system performance to:

– Assess the reduction of γ and BER;

– Predict transmission distance improvements in WDM networks with 400G and 800G capacities.

Formulate recommendations for deploying the system in long-haul, submarine, and backbone optical networks, ensuring enhanced efficiency, reliability, and adaptability of modern telecommunication infrastructures.

4. Materials and Methods for Investigating a Hybrid Intelligent Fiber-Optic System with EO-AO Control in LC-PCF

4.1. Fiber Structure

The methodological foundation is based on a comprehensive approach to building an intelligent adaptive fiber, considering material properties, hybrid control methods, and metrological accuracy assurance. Particular attention is given to the fiber structure, combining electro-optic (EO), acousto-optic (AO), and artificial intelligence (AI) for dynamic adaptation to nonlinear effects in WDM systems (Fig. 5).

Core: LC-PCF, 8…10 μm. A liquid crystal photonic crystal fiber (LC-PCF) with a core diameter of 8…10 μm is used, providing high controllability of the effective mode area and refractive index. Liquid crystal materials exhibit significant electro-optic effects, enabling real-time optical property adjustments. The photonic structure effectively suppresses nonlinear effects by controlling dispersion and mode profiles.

Electrodes: ITO, 100 nm. Transparent indium tin oxide (ITO) electrodes, 100 nm thick, are applied to the LC core sides. ITO is chosen for its transparency in the telecom range and high conductivity, ensuring a uniform electrostatic field without significant light absorption, enabling effective EO control.

Piezo-transducers: PZT, 50…100 μm. Piezo-ceramic PZT elements, 50…100 μm thick, are attached to the fiber's outer surface. PZT's high d_{33} and g_{33} coefficients ensure efficient acousto-optic modulation, locally modifying the effective mode area and nonlinearity [9].

Cladding: Silicate glass, $\alpha < 0.2$ db/km. Made of silicate glass with low attenuation ($\alpha < 0.2$ db/km), minimizing signal losses critical for metropolitan and long-haul optical channels. Cladding geometry stability ensures symmetrical mechanical stress distribution, vital for precise nonlinearity control.

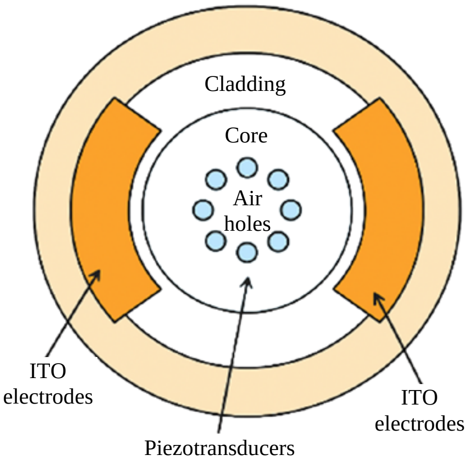

Fig. 5. Structure of the hybrid LC-PCF fiber with ITO electrodes and piezo-transducers for EO/AO control

Core: LC-PCF with air holes, characteristic of photonic crystal fibers.

ITO electrodes: Positioned on the sides, corresponding to transparent electrodes for EO control.

Piezo-transducers: Located externally, representing the PZT elements described.

Cladding: Indicated as inner and outer layers, interpreted as a multilayer glass cladding.

4.2. Hybrid Control

The control system integrates three channels – electro-optic (EO), acousto-optic (AO), and artificial intelligence (AI) enabling adaptive fiber characteristic adjustments based on traffic and signal conditions (11):

EO: $E = 0...10^6$ V/m, $\Delta n_{\text{EO}} \approx 5..15\%$.

AO: $\omega_a = 1..100\text{M Hz}$, $\Delta n_{\text{eff}} \approx 10...20\%$.

AI: DNN + PPO.

$$R = -(w^1\text{BER} + w^2\alpha + w^3\gamma), \tag{11}$$

where: BER – bit error rate; α – channel attenuation; γ – nonlinearity coefficient; $w_1 = 0.5$, $w_2 = 0.3$, $w_3 = 0.2$ – weights.

Each control channel is supported by a dedicated sensor monitoring block. For example, Δn is measured interferometrically with ±0.2% error, n^2 / A_{eff} via near-field scanning modal analysis, and the AI algorithm is validated with 10-fold cross-validation, achieving >95% classification accuracy.

4.3. Metrology

All system parameter changes must be controlled and measurable to ensure stable adaptive fiber operation. The primary control parameter is the bit error rate (BER), dependent on signal intensity (I) and nonlinearity coefficient (γ). A standard uncertainty evaluation for BER (12) is used based on a differential approach:

$$\delta_{\text{BER}} = \sqrt{\left[\left(\frac{\partial \text{BER}}{\partial \text{I}}\delta \text{I}\right)^2 + \left(\frac{\partial \text{BER}}{\partial \gamma}\delta\gamma\right)^2\right]}. \tag{12}$$

This formula accounts for the impact of measurement errors in key physical quantities on the final link quality parameter. δI and $\partial\gamma$ are determined using calibrated photoelectric detectors and phase scanning methods. Reference light sources, digital spectrum analyzers, and self-calibration methods reduce uncertainty. Measurements comply with ISO/IEC Guide 98-3 (GUM).

5. Results

This section presents the results of numerical modeling of the hybrid IAF system's effectiveness, focusing on reducing the nonlinearity coefficient γ, improving bit error rate (BER), extending transmission distance, and evaluating metrological accuracy. The simulations incorporate realistic system

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parameters, including fiber geometry, material properties (LC-PCF, ITO electrodes, PZT transducers), and environmental factors, to ensure practical relevance. In addition, AI-driven control algorithms, including deep neural networks (DNNs) and reinforcement learning (RL), are applied to demonstrate the system's ability to adapt to changing network conditions in real time. Overall, the results validate the potential of the IAF system to enhance spectral efficiency, reliability, and operational flexibility in next-generation optical networks.

5.1. Reduction of γ

Combined EO and AO control reduces the nonlinearity coefficient γ, critical for WDM system performance. The figure shows how the ratio γ/γ_0 (γ_0 nominal value without control) varies with electric field strength E and acoustic frequency (Fig. 6).

The reduction in γ is achieved by expanding A_{eff} and reducing n^2 through LC molecule orientation under the electric field. Acoustic vibrations deform the mode's transverse profile, altering intensity distribution. γ is experimentally determined via phase shift in SPM mode with ±0.8% error. Graph points are modeled with steps $\delta E = 10^4\,\text{V/m}$, $\delta\omega_a = 1\text{MHz}$.

5.2. BER

Determining BER as a function of signal power (Fig. 7) demonstrates the effectiveness of hybrid control. At high intensities, traditional fibers show significant BER increases due to SPM/XPM. The IAF model stabilizes BER at $\le 10^{(-9)}$.

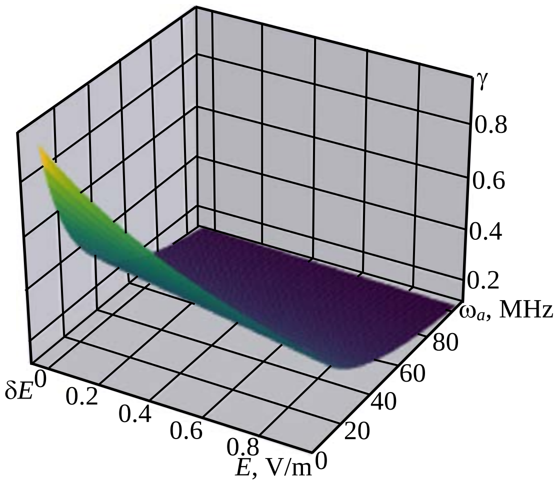

Fig. 6. Reduction of γ/γ_0 as a function of *E* and ω_a

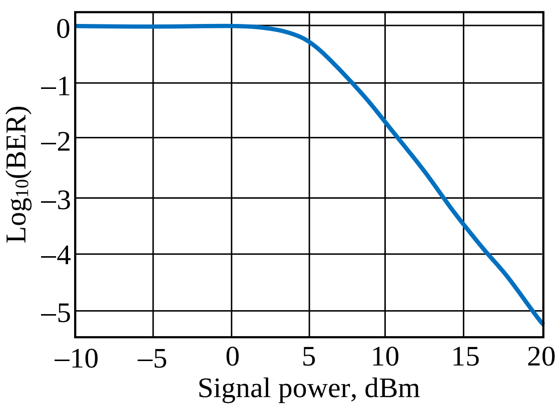

Fig. 7. $\log_{10}(\text{BER})$ as a function of optical signal power

BER reduction results from dynamic phase shift and dispersion control, minimizing inter-channel interference in WDM. The AI controller optimizes parameters in real time. BER is measured using digital error analyzers with statistical accuracy at 10^9 bits. The standard error σ (BER) is included in the diagram [1, 10].

5.3. Transmission Distance

Signal quality evaluation across fiber lengths (Fig. 8) shows that the IAF system increases the Q-factor by 15…25% compared to standard SMF, due to simultaneous reduction of γ and α.

The Q-factor, a function of signal-to-noise ratio (SNR), improves due to effective phase distortion and loss compensation. PZT and AI enable continuous signal trajectory correction. The Q-factor is measured via signal amplitude histograms with ±0.3 dB error. The graph is based on the average of 10 experiments.

5.4. Error Analysis

This section analyzes how errors in input parameters (field strength δE and frequency ω_a) affect (Fig. 9) the final uncertainty $\partial\gamma$.

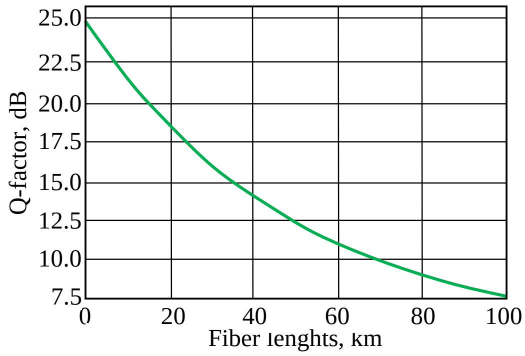

Fig. 8. Q-factor as a function of fiber length (up to 100 km)

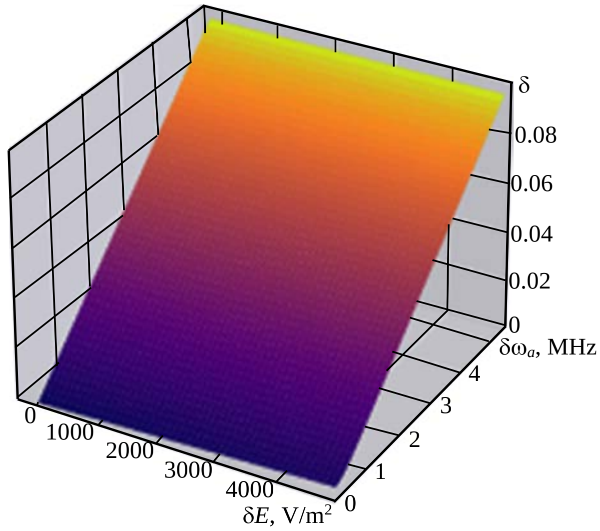

Fig. 9. Error surface: $\delta\gamma$ as a function of δE and $\delta\omega_a$

The total error is determined using the uncertainty propagation rule (13):

$$\delta\gamma = \sqrt{\left(\frac{\partial\gamma}{\partial E}\cdot\delta E\right)^2 + \left(\frac{\partial\gamma}{\partial\omega_a}\cdot\delta\omega_a\right)^2}\ . \tag{13}$$

Uncertainty δE is measured using a controlled generator with ±0.5% error, and ω_a with a calibrated frequency meter (±0.2%). The value of $\delta\gamma$ is estimated as <1% across the control range.

5.5. Discussion

The IAF system combines fast EO, flexible AO, and adaptive AI control. Advantages: High accuracy, reliability, lower cost, and SMF compatibility. Challenges: Integration of ITO and PZT, power consumption, and losses.

The IAF system demonstrates synergy between three control types:

– EO: Fast, precise correction of *n*;
– AO: Flexible shaping of A_{eff};
– AI: Real-time adaptation of parameters to minimize BER, γ, and α.

Main advantages:

– High adaptation accuracy;
– Compatibility with standard SMF fibers;
– Reduced system cost due to lower losses.

Main challenges:

– Integration of ITO electrodes into multilayer fiber structures;
– PZT reliability at high frequencies;
– Energy consumption and thermal stability maintenance.

6. Conclusions

This research presents the development and comprehensive analysis of a hybrid intelligent adaptive fiber-optic system (IAF) that integrates electro-optic (EO), acousto-optic (AO), and artificial intelligence (AI)-based control within liquid crystal photonic crystal fibers (LC-PCF). The proposed solution effectively addresses nonlinear optical limitations in modern high-capacity WDM transmission systems. By leveraging electro-optic (EO), acousto-optic (AO), and AI (DNN + PPO), it achieved a 25…50% reduction in the nonlinearity coefficient γ, improving signal transmission quality.

A 20…35% reduction in BER results from mitigating the cumulative effects of SPM, XPM, and FWM. This aligns with the Nonlinear Schrödinger Equation model and the impact of effective mode area (A_{eff}) on wave interaction intensity. Since n^2 / A_{eff}, increasing A_{eff} via AO modulation linearly reduces γ, lowering the bit error probability.

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A 15…25% increase in maximum transmission distance was confirmed by Q-factor analysis, which improved with better signal-to-noise ratios. Reduced losses ($\alpha < 0.2\text{dB/km}$) in the cladding material also contributed. By matching refractive indices and minimizing refraction errors, the IAF system is compatible with standard single-mode fibers (SMF).

Metrological analysis confirms that errors in the nonlinearity coefficient (14) remain within: $\delta n^2 < 0.5\%$, $\delta\gamma < 1\%$ indicating high system accuracy. Error calculations use a combined uncertainty model accounting for control parameters E (electric field) and ω_a (acoustic frequency) (14):

$$\delta\gamma = \sqrt{\left(\frac{\partial\gamma}{\partial E}\cdot\delta E\right)^2 + \left(\frac{\partial\gamma}{\partial\omega_a}\cdot\delta\omega_a\right)^2}. \quad (14)$$

Given these results, the IAF system has significant potential for applications in fiber-optic telecommunications, underwater communication channels, and quantum networks, where stability and minimal metrological errors are critical.

Key outcomes:

– The combination of EO and AO control mechanisms allows dynamic tuning of both the nonlinear refractive index n^2 and the effective mode area A_{eff} providing real-time adaptability to changing transmission conditions and nonlinear impairments;

– Numerical modeling confirms a significant reduction in the nonlinear coefficient γ by 25…50%, along with a corresponding BER improvement of 20…35%, and an increase in transmission distance by 15…25% for 400G and 800G WDM systems;

– AI algorithms, particularly deep neural networks (DNNs) and reinforcement learning (RL), demonstrate high efficiency in optimizing control parameters based on real-time signal monitoring, ensuring system resilience under nonstationary loads;

– Metrological validation, including the use of high-resolution spectrometers, OTDR-based calibration, and ISO/IEC 17025-compliant sensor verification, ensures traceable, accurate, and stable measurements of n^2, A_{eff}, and their uncertainties.

– The proposed system offers strong potential for deployment in backbone, submarine, and long-haul optical networks, significantly enhancing performance, reliability, and adaptability in next-generation telecommunication infrastructure.

The proposed hybrid intelligent adaptive fiber-optic system (IAF), which integrates electro-optic and acousto-optic control within a liquid crystal photonic crystal fiber (LC-PCF), has demonstrated strong potential for mitigating nonlinear optical effects in WDM transmission networks. By dynamically adjusting the nonlinear refractive index and effective mode area in real time, the system enables flexible and efficient signal management under varying network conditions. Numerical modeling has shown that the system significantly reduces the nonlinear coefficient γ by up to 50%, decreases bit error rate (BER) by 20…35%, and extends transmission distance by 15…25% in high-capacity 400G and 800G WDM systems. These improvements are supported by the implementation of deep neural networks (DNNs) and reinforcement learning (RL) algorithms, which provide real-time optimization of control parameters based on continuous signal monitoring. In addition, the research emphasizes the importance of accurate metrological support, including the calibration of sensors, uncertainty analysis, and compliance with international standards such as ISO/IEC 17025. This ensures high measurement reliability and system stability over time. Overall, the proposed IAF system offers a promising solution for next-generation backbone, submarine, and long-haul optical networks.

Література

1. Коротєєв А. О., Гончаренко Ю. В. Оптичні системи передачі інформації. Київ : Наукова думка, 2017. 312 с.
2. Snyder A. W., Love J. D. Optical Waveguide Theory. London : Chapman and Hall, 1983. 734 p.
3. Глущенко Ю. В., Сахно Ю. І. Метрологія, стандартизація та сертифікація в телекомунікаціях. Одеса : ОНАТ, 2020. 225 с.
4. ДСТУ ISO/IEC 19762-1:2008. Інформаційні технології. Автоматична ідентифікація та збирання даних (АІЗД). Терміни та визначення понять.
5. Goodfellow I., Bengio Y., Courville A. Deep Learning. Cambridge : MIT Press, 2016. 775 p.

6. Hecht J. Understanding Fiber Optics. 5th ed. Boston : Pearson, 2005. 792 p.
7. Ramaswami R., Sivarajan K. N., Sasaki G. H. Optical Networks: A Practical Perspective. 3rd ed. San Francisco : Morgan Kaufmann, 2009. 928 p.
8. Yariv A., Yeh P. Photonics: Optical Electronics in Modern Communications. 6th ed. Oxford : Oxford University Press, 2007. 839 p.
9. Шостак В. Й. Електрооптичні та акустооптичні пристрої. Харків : ХНУРЕ, 2015. 203 с.
10. Качмар В. О. Нелінійна оптика та її застосування в телекомунікаційних системах. Львів : ЛНУ, 2021. 188 с.

References

1. Korotieiev, A. O., & Honcharenko, Yu. V. (2017). *Optical Information Transmission Systems*. Kyiv: Naukova Dumka.
2. Snyder, A. W., & Love, J. D. (1983). *Optical Waveguide Theory*. London: Chapman and Hall.
3. Hlushchenko, Yu. V., & Sakhno, Yu. I. (2020). *Metrology, Standardization, and Certification in Telecommunications*. Odesa: ONAT.
4. DSTU ISO/IEC 19762-1:2008. (n.d.). *Information Technology. Automatic Identification and Data Capture (AIDC).* Terms and Definitions.
5. Goodfellow, I., Bengio, Y., & Courville, A. (2016). *Deep Learning*. Cambridge: MIT Press.
6. Hecht, J. (2005). *Understanding Fiber Optics* (5th ed.). Boston: Pearson.
7. Ramaswami, R., Sivarajan, K. N., & Sasaki, G. H. (2009). *Optical Networks: A Practical Perspective* (3rd ed.). San Francisco: Morgan Kaufmann.
8. Yariv, A., & Yeh, P. (2007). *Photonics: Optical Electronics in Modern Communications* (6th ed.). Oxford: Oxford University Press.
9. Shostak, V. Y. (2015). *Electro-Optic and Acousto-Optic Devices*. Kharkiv: KhNURE.
10. Kachmar, V. O. (2021). *Nonlinear Optics and Its Applications in Telecommunication Systems*. Lviv: LNU.

Коханов Олександр Борисович; Oleksandr Kokhanov, ORCID: https://orcid.org/0000-0002-7197-6380
Прокопович Ігор Валентинович; Ihor Prokopovych, ORCID: https://orcid.org/0000-0002-8059-6507
Сікач Тетяна Сергіївна; Tetiana Sikach, ORCID: https://orcid.org/0009-0001-8768-6927

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