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Analysis on current opto-electronic transmission research and its materials with new perspectives

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Abstract. Opto-electric transmission technology serves as a basis for today's fast developing telecommunication, digital transmission and information processing. As the global community becomes more digitalized, there is a growing expectation for more convenient communication, information security, and ultra-fast data processing. This paper overviews recent works of opto-electric transmission including theoretical analysis, material construction, structural improvement of transmission apparatus and encryption schematics. In addition, a comparison of the wire and wireless transmission approach and analysis on the relationship between transmission performance indicators and influencing factors are presented. Progress and limitations of current opto-electric technology are discussed in the context of underlying principles and mechanisms. Prospect vision on trends of opto-electronic research in the near future is presented. In the future, opto-electric transmission is expected to possess higher speed, efficiency and security. This review paper aims to provide a picture of current research teams' investigation focus and the present status of opto-electric transmission.

Keywords: opto-electric transmission, wired and wireless transmission, data processing, performance indicator.

1. Introduction

Research in opto-electric transmission primarily involves investigation in optics, electronics, semiconductors, spectroscopy and charge carrier statistics. Its development builds upon advancement in electromagnetism, photonics, quantum physics theories, material exploration of photoelectric properties, and device structure engineering. The various achievements of this technology directly benefit applications in communication, healthcare, transport system, auto-industry, information security and many other fields. Recent development in the opto-electric transmission is carried out in the context of foundational theories regarding light matter interaction, photo-electric transition, and quantum statistics which determine how signals are generated, transmitted and processed. Building upon these theories, many device components of opto-electric transmission system are developed over decades such as antenna systems, waveguides, resonators, photodiodes, lasers, etc. The progress in opto-electric technology is closely associated with the demand for faster, safer and more efficient data transmission. Therefore, understanding the functions of different compositions, structures in opto-electronic apparatus

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and underlying principles is of great importance to researchers interested in developing opto-electrical technologies.

This paper aims to present a general review of current hindrances and recent advancements in the field of optoelectronics, followed by a prospective vision of a near-future research focus. The first section is an overview of modern opto-electric transmission technologies, with the development of new materials, structures and theories in broadcasting, communication, detection and measurement [1-5]. The following section recounts research of recent 5 years on wire or wireless transmission, in which comparative analysis is conducted between these two transmission approaches regarding their transmission rate, cost and coverage range to provide a comprehensive description of their current status and developing trends [6-8]. The third section introduces key indicators of opto-electric transmission performance and analyzes how they are influenced by external conditions. Lastly, a prospective vision of opto-electric transmission is given to demonstrate future development trends of materials, system structures and scheme designs, which portray how current limitations may be addressed and potential applications stemming from current research.

2. Frontier opto-electric material development and system structure design

Opto-electrical transmission is not only limited to sending signals via optical or electrical waves, and a key process is a conversion between optical and electrical energy. This process is typically associated with electron energy transition models. Some of the opto-electric processes are unstable which eventually transform to a steady state. Petrov et al. used ZnPc-flourophore-based transistor to demonstrate the transformation from transient to stationary optoelectronic process, an approach to analyze temporal and stationary behavior of current and electron luminescence [1]. Unlike the study of stationary transmission, transient optoelectronic processes in photo-active lacked sufficient experimental data, and this blank was filled by the work of Petrov et al., including derivation of analytical expression of overall rates, demonstration of temporary reorganization of transmission channel as well as a radiative and non-radiative transition [1]. Their work introduced an Electrode-molecule-electrode (1M2) structural system, or photo-active mono molecular transistor that increased the order of light emission by more than one magnitude through the generation of plasmon. Their work also used photoactive planar molecule's models (ground singlet, excited triplet, excited singlet, cation, anion states) in quantitative analysis. The non-radiative intramolecular singlet-singlet transition was discussed, where one mechanism of inter-electrode electron transfer was direct inter-electrode electron tunneling and the electronic state of molecule in this route could either be maintained or altered (altered referred to as inelastic electron tunneling, which promoted transition by quenching electron luminescence and Inter System Crossing) [1]. They then analyzed electron transmission using kinetic equations which demonstrated that transient processes can be characterized by changes in molecular states from non-monotonous states to steady states, and described how specific molecular states and transitions affected the characteristic time of stationary transmission [1].

Another device that operates by emission and reception of light is the photoelectric sensor, and many of its performances can be traced to the physical properties of photo-electrical materials used. One recent study of such materials was conducted by El-Newehy et al.. This study used spin coating to fabricate dyed chitosan thin film and determined its suitability for photo-sensing through responsivity and specific detectivity values [2]. The main value of chitosan is that its optoelectrical property can be tuned via modulated dyeing process since some dyes have varied transmittance and reflectivity and are suitable for optical shielding or filtering. The engineered film had a hybrid hetero-junction configuration (metal/insulator/semiconductor) and its high absorbance in UV and visible range was suitable for absorbance enhancer. Moreover, using Ag/Cs-MV/p-Si electrode and plasmonic nanoparticles could significantly increase the responsivity, detectivity, conductivity and light capturing efficiency of photoelectric sensors [2]. This was validated by measurements of Ag/Cs-MV/p-Si which had a density of interface trapping state of 3.56×10^{-13} $eV^{-1}cm^{-2}$, photocurrent of 0.29 mA/cm^2, responsivity of 3.05 mA/W, and detectivity of 5.79×10^8 D*. Plasmonic nanoparticles can be manipulated through altering dipole distribution and oscillation frequency of its electrons with polarized electro-magnetic radiation,

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leading to an adjustment of optical and electrical properties that could effectively increase light capturing efficiency and conductivity. The development of such film could potentially be part of commercialized photoelectric sensors and solar cells and pose less harm to the environment compared with most metal and ionic pieces currently in use.

An optical diode is mainly responsible for controlling the path of optical waves and the safe isolation of different circuit sections. Its working principle can be traced back to the interaction of the magnetic field with the optical wave; it can be categorized into polarized type, composite type and magnetic type, and can be connected to optical amplifiers, ring filters, etc. Xu et al. developed an efficient optical diode with a high non-reciprocal transmission ratio (NTRs) and low power consumption by employing two cascaded all-silicon opto-mechanical microring resonators (MRRs) [3]. Different resonance red-shifts occur in two MRRs and result in asymmetric transmission spectra, resulting in a unidirectional optical signal at ultra-low input power [3]. Silicon diode's NTRs could be further increased by placing MRRs at the critical coupling [3]. The construction of this diode is an exemplary example to improve transmission performance in signal modulation and optical communication systems.

Other extended branches of opto-electric transmission include detection, processing, encryption and automated system which also attract increasing interest from research labs and corporations. For instance, one article in 2019 proposed a strap-down stability control scheme for opto-electric systems that involved a proportional integral controller (PI) and a state augmented Kalman filter (SAKF) [5]. This scheme excelled in mending nonlinear torque disturbance and speed estimation, which led to enhanced low speed performance and inertial stability accuracy of opto-electric servo systems [5]. The proposed scheme is one effort to upgrade the sensing and imaging capability of Airborne detectors of optical frequency from visible to microwave range. With more and more aspects of work and life being digitized in the modern community, safe preservation and transport of information become more vital. This demand is being addressed by the creation of complex encryption schemes, one of which is proposed by Cyriac and Sheeja, a novel approach to secure transmission and reception of digital data with opto-hybrid technique of two-stage encryption [4]. The technique was based on optical scanning cryptography and Fibonacci-Lucas transformation and utilized a point-spread function as a new key generated from a fused biometric array and digital encryption method [5]. Cyriac and Sheeja anticipated the scheme to benefit radio-graph image transfer for medical treatment using telecommunication technologies [4]. As for automated systems designed for an industrial upgrade, the main focus is on optical bus technology, which simulates the function of bus systems on core processing units to allow fast data transmission in organized channels among modules. Developing new schemes for optical bus systems could potentially lead to revolutions in motion control, production line maintenance, and redistribution of network cables responding to industry module update with minimal latency (parallel control).

3. Wired and wireless transmission

Opto-electric transmission can also be classified into wired and wireless transmission approaches. Common wired transmission has a few comparative advantages: more resistance to noise and interference, high stability in preserving signals, combining ultra-wide bandwidth and fast transmission rate. The disadvantage of wired transmission is mostly associated with the reliance on cable and fiber, which means such devices are confined by geographical conditions, immobility and cost associated with laying and maintaining transmission cables.

On the other hand, wireless transmission has high mobility, wide coverage regardless of geographical location and elimination of cable construction. Its limitation is also obvious: comparatively weak resistance to noise and interference, slower transmission rate and finite bandwidth, though these drawbacks are being amended with emerging technologies.

Recent structural improvement of wireless transmission systems has greatly increased its transmission bandwidth and power efficiency both of which were considered drawbacks of wireless communication. Prather et al. designed an opto-electronic architecture based on Fourier Optics consisting of analog that transmits and receives implementation using optical up/down conversion [6].

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It was assessed to have low power consumption and negligible latency (optical beam performing using lens) and near unlimited beam-bandwidth product with no need for external cooling [6]. Their article pointed out some limitations. 1. Most present wireless communication relied on Base Transceiver Station (BTS) to satisfy simultaneous Multi-band, multi-beam, multi-sector transmission. 2. Current all-electronic systems were limited in maintaining synchronicity of antenna elements at high carrier frequencies. 3. Fully digital beam-forming solutions were limited by their high cost and power consumption 4. Microwave In-phase quadrature up-converters were restrained by power and phase imbalance and relatively narrow operating bandwidth [6]. To address these limitations, the article proposed an implementation design which includes a common optical module that reduces the count number of radio frequency (RF) components (new Base Transceiver Station architecture) [6]. While adjusting the antenna array of the Base Transceiver Station to suit the frequency of radio bands improved wide-spectra, multi-band operation, photonic up/down conversion processed RF waveform of high quality as high frequency amplifiers and up-converting modulators of receiver functioned in series with transmitter's photo-diodes and electronic processing occurred only at a low intermediate frequency [6]. For conventional structure, digital processing took place within base-band unit and both radio/intermediate frequency processing and base-band processing are required in RF processing unit; in hybrid E/O architecture, Digital-to-analog converters were moved from based-band unit to RF processing unit, and no base-band processing was required in RF processing unit [6]. Lemey et al. tackled the issue of the integration of antenna system structure and published their work in 2020. They integrated micro-wave photonic, radio-over-fiber (ROF), air-filled-substrate integrated waveguide (AFSIW) technology to achieve large-scale and highly integrated multi-antenna system, and described two designs of AFSIW-based photonic-enabled remote antenna units to boost power transfer efficiency: a Distributed impedance matching network that converted the antenna impedance to match photo-diode's output impedance and a hybrid integration and conjugate matching of broadband mmWave antennas, where air-filled AFSIW cavity enabled antenna elements to possess required input impedance [7]. ROF reduced the cost and complexity of wide-band signal transmission from central units to remote antenna units by the concentration of hard wares on the central unit, and compact antenna structure minimized mutual coupling (electromagnetic interaction between antenna units), which affects array radiation pattern and input impedance of the individual antenna [7].

The wired transmission itself can also be classified into multiple types, in which serial transmission and parallel transmission appear most often. In serial transmission, data is transferred in two directions, continuously from one-bit unit to the next through a communication channel over a long distance. On the other hand, parallel transmission transfers multiple (e.g. 8) bits simultaneously per clock cycle via computer bus or to a device nearby. Serial transmission usually has a smaller update rate but is more economical; parallel transmission's faster clock rate requires a uniform length of individual wires representing each parallel bit, or the signal would be distorted.

Optical fibers can be classified by the distribution of refractive index: multi-mode fiber has graded mode, and the refractive index of the medium decreases gradually from centre to edge; for stepped fiber, the refractive index of the medium decreases abruptly at the coating surface, and normally has narrower bandwidth. A useful component for wired transmission is the microring modulator. It modulates optical waves by the following process: light enters the closed loop from the input waveguide and then circulates the loop multiple times via total internal reflection; for a few wavelengths, in-phase constructive interference is built up during circulation before being outputted to the detector waveguide. It is a key component in wavelength division systems, and frequency modulation which encodes data on carrier optical waves. A new type of microring modulator was implemented Moralis-Pegios et al. for long-distance wired transmission. This modulator of O band silicon had modulating rates up to 50 Gb/s through 52 km long standard single mode fiber, supported 40 Gb/s data transmission at 10^{-9} error rate and negligible power penalty, and at 50 Gb/s transmission required only 20% of driving voltage level compared with $LiNO_3$ modulator commercially in use [8]. CMOS driver operating at ultra-low input electrical signal was also implemented to guarantee high band-width distance product while removing the need for chromatic dispersion compensation [8].

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4. Opto-electric transmission performance indicators and relations to external factors

This section analyzes correlations between important opto-electric transmission indicators and influencing factors.

1) Optical power: measured in dBm, reference power 1 milliwatt, and corresponds to heating power of optical wave emission end.

2) Extinction ratio (ER): the electrical power to optical power conversion efficiency of an optical transmitter for high-speed digital communication. A high extinction ratio correlates to a lower power penalty, and longer fiber distance.

3) Bit-error-rate (BER): a key indicator of system performance, defined as the ratio of an expectant number of errors generated and the expectant number of bit information transmitted within the same time period. This indicator correlates negatively with the extinction ratio and increases with noise and signal attenuation.

4) Dielectric loss: dissipation of electrical energy to thermal energy heating dielectric material when charges travel in an electrical field. Typical materials with low dielectric loss are PTFE, alkali earth metal compounds, silicon compounds, etc. (Some examples are shown in Table 1) External applied magnetic field would interact with charge flow within a dielectric material, leading to heating.

5) Channel spacing: standard carrier frequency difference of two adjacent transmission channels.

6) Optical Fiber dispersion: limiting factor of transmission distance and data transfer rate of optical fiber communication system. Its sub-classification includes conditions of mode dispersion, waveguide dispersion, and chromatic dispersion. The refractive index increases as the ion's dielectric constant increases, is influenced by material micro-structure, and relates to the internal stress vector.

7) Effective nonlinear coefficient: the ratio between the product of optical power and fiver distance and phase changes in transmitted waves. It is proportional to the nonlinear Kerr index (Typical example shown in Table 1) and inversely proportional to the effective mode area. Appropriate procedures of nonlinear coefficient measurements were recently investigated by Vermeulen (2023) [9].

Table 1. List of nonlinear Kerr index and dielectric loss value for typical materials.

Type of material	graphene	air	silica fibers	optical crystals
Nonlinear index m^2/W	10^{-11}	$5*10^{-23}$	$3*10^{-18}$	$9*10^{-17}$
Type of material	glass	PTFE	polyimide	LCP
Dielectric loss (Df)	$2*10^{-2}$	$4*10^{-4}$	$8*10^{-3}$	$2*10^{-3}$

Besides the above indicators, Fidelity is an important quantity in quantum teleportation which manipulates photons as chronically stable superposition states for photonic qubits. It measures how close the applied quantum state used to generate quantum bits is to the ideal state. Luo et al. (2020) proposed a scheme which could transfer the quantum state (Einstein-Podolsky-Rosen) from optical input to microwave output at high Uhlmann fidelity at various frequency bands. Ulhmann fidelity describes the efficiency of quantum state transfer, which also quantifies the performance of the EPR scheme [10]. In their article, the principle and operation modes of cavity electro-opto-mechanical (EOM) microwave converter were discussed, and the influence of optical input bandwidth and coupling rates on fidelity, transmission spectrum, interaction rate, and decoherence rate were analyzed [11]. The cavity EOM converter had a structure where an optical F-P cavity and a microwave LC circuit cavity were coupled with a nano-scale mechanical oscillator consisting partial circuit on a movable silicon plate, which functioned in microwave optical entanglement transmission mode (detuning of microwave frequency equals to detuning of optical frequency equals to mechanical oscillator frequency, $\Delta M = \Delta O = \omega_{\mathrm{m}}$) or state transfer mode ($\Delta M = -\Delta O = \omega_{\mathrm{m}}$) [11]. The article also showed that strong coupling rates, ultra-low temperature and narrow input bandwidth improved the performance of this scheme and indicated relevant fields of implementation including quantum computing, quantum communication network and quantum interface [11].

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5. Proposal of improvement and prospective vision

For wired communication, there are three approaches to address optical fiber dispersion: (1) dispersion compensating fiber, which introduces fiber of negative dispersion so that total dispersion of fiber system is minimized; (2) implementing fiber Bragg grating, which reflects light pulses that meet modulation condition while letting rest to pass through; (3) electron dispersion compensation, which uses self-adaptive wave filter to compensate signal attenuation. For outdoor communication devices, dust, moisture and acidity environment undermine the stability of circuits, and the selection of sealed, airtight sensors with mechanically and chemically stable coating materials is crucial. Innovative signal transmitting network structure has great potential to improve the response speed and communication rate of next-generation wireless systems [12]. For modulators and wave guides, materials and structures should possess high thermal conductivity in order to minimize impact from heat due to dielectric loss. Semiconductor components need low relative permittivity to achieve low electrical signal speed delay due to resistance and capacitance. A way to improve the signal transmission quality is to increase the extinction ratio, which can be achieved by the implementation of optical modulators which reduce noise signals by controlled interference. Quantum teleportation is the likely answer for secure communication, though more advancement in information transmission rate needs to be made for commercial and civil use.

6. Conclusion

Current research in opto-electrical transmission technology is carried out in a rapidly expanding digital global community with an increasing demand for convenient, ultra-fast, broad band, multichannel, and secure information transmission. This paper reviews various approaches to achieve more powerful opto-electric sensing, communication, and processing: development of artificial material compounds; new structure in sensors diodes, antennas and other opto-electric components; scheme designs upgrading system functionalities, etc. Key indicators in opto-electric transmission and their relations to other factors are introduced and analyzed before presenting improvement proposals. Given the rapid renewal in opto-electric transmission, further progress is expected in performance aspects such as data rate per channel, stability from noise and interference, mitigation of fiber dispersion and linear/nonlinear impairment, receiver sensitivity, etc. These limitations to some extent may be addressed by optical modulation formats, division multiplexing, digital amplifiers or waveguides, though more solutions are being developed. In the near future, wire and wireless transmission would both retain their importance as new transceiver system architecture, waveguide and modulators are being developed. Emerging encryption schemes, material fabrication methods, and theoretical progress in fields such as Fourier optics provide a promising vision of eco-friendly, multi-band, more power efficient, and secure opto-electrical communication layout.

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