



Material-Specific Effects on Ultrafast Optical Signal Processing A Comprehensive Study of ZnO and TiO₂

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ABSTRACT

All-optical signal processing (AOSP) facilitates the direct manipulation of optical signals, thereby circumventing electro-optic conversion and minimizing latency while enabling functions such as switching and modulation at ultrahigh speeds. This study assessed zinc oxide (ZnO) and titanium dioxide (TiO₂) as ultrafast nonlinear optical media for AOSP and compared their nonlinear response dynamics, considering practical constraints. Material preparation involved combustion and sol-gel synthesis for ZnO, and sol-gel and atomic-layer deposition for TiO₂, followed by structural and optoelectronic characterisation. Ultrafast dynamics were examined using femtosecond pump-probe spectroscopy with nonlinear detection and D-SP-based reconstruction, evaluated through exponential fitting and electromagnetic modelling. ZnO demonstrated faster rise/decay dynamics and sharper transient absorption peaks compared to TiO₂, indicating higher carrier mobility, whereas TiO₂ exhibited broader spectral signatures and prolonged responses. ZnO displayed unconventional decay features, suggesting multiple recombination pathways, whereas TiO₂ showed excitation-intensity-dependent temporal elongation, necessitating models incorporating multiphoton absorption and carrier dynamics. ZnO is promising for ultrafast photonic applications, whereas TiO₂ may be suitable for hybrid architectures where sustained charge separation is advantageous; however, widespread adoption requires enhanced defect control and interface engineering.

Keywords: zinc oxide, titanium dioxide, ultrafast nonlinear optics, femtosecond pump-probe spectroscopy, nonlinear optical materials, optical switching, and modulation.

A. INTRODUCTION

a. Background on all-optical signal processing: All-optical signal processing has emerged as a critical technology for advancing high-speed communication systems, which demand rapid data transmission and minimal latency to support the growing needs of modern information networks. Optical materials with ultrafast nonlinear responses are key to achieving this performance, as they allow for rapid modulation and switching of light signals. Optical materials with ultrafast nonlinear responses are key to achieving this performance, as they allow for rapid modulation and switching of light signals. Among the promising candidates for such applications are zinc oxide (ZnO) and titanium dioxide (TiO₂), which exhibit favourable optical properties, including strong nonlinearities and fast response dynamics, making them suitable for integration into all-optical signal processing devices.

b. Research objectives and significance: This study aims to investigate the nonlinear optical properties of zinc oxide (ZnO) and titanium dioxide (TiO₂) to evaluate their suitability for all-optical signal processing applications. The main research question focuses on how these materials' ultrafast response times and nonlinear behaviors can be optimized to enhance the performance of high-speed optical communication systems. The relevance of this study to the field of physics lies in its contribution to understanding light-matter interactions at ultrafast timescales and nonlinear optical phenomena in semiconductor and dielectric materials. The relevance of this study to the field of physics lies in its contribution to

understanding light-matter interactions at ultrafast timescales and the nonlinear optical phenomena in semiconductor and dielectric materials. The potential applications of the findings extend to improving the speed, bandwidth, and energy efficiency of communication networks, optical computing, and signal processing technologies. The potential applications of the findings extend to improving the speed, bandwidth, and energy efficiency of communication networks, optical computing, and signal processing technologies. By demonstrating the practical viability of ZnO and TiO₂ in all-optical devices, this research could significantly impact the design of faster, more compact, and scalable photonic components, thereby accelerating progress in telecommunications and information processing industries. The theoretical implications of the findings from this study provide significant insights into the nonlinear optical behaviors of zinc oxide (ZnO) and titanium dioxide (TiO₂), contributing to the broader understanding of light-matter interactions at ultrafast timescales. The results not only support existing theories regarding the nonlinear response mechanisms in semiconductor and dielectric materials but also challenge certain assumptions about the limits of response speed and efficiency in these systems. By revealing nuanced dynamics in the optical switching and modulation processes, this research proposes modifications to current theoretical models, suggesting new pathways to describe the interaction between intense optical fields and material electronic structures more accurately. These refined models enhance the fundamental comprehension of nonlinear optics, particularly in the context of all-optical signal processing, where rapid and efficient control of light is paramount. The study's findings also encourage re-examination of established frameworks, potentially leading to the development of more comprehensive theories that incorporate the observed phenomena, such as multi-photon absorption effects, carrier dynamics, and defect-related nonlinearities in ZnO and TiO₂. This theoretical advancement not only enriches the physics community's conceptual toolkit but also lays a solid foundation for future experimental and computational investigations aimed at optimising material properties for photonic applications.

From a practical perspective, the implications of these findings are profound for the advancement of high-speed communication systems. The ultrafast nonlinear responses and efficient optical switching capabilities demonstrated for ZnO and TiO₂ suggest that these materials can be effectively integrated into next-generation photonic devices, potentially overcoming current bottlenecks related to speed, energy consumption, and miniaturisation. The scalability of these materials for industrial applications is promising; however, the study also acknowledges challenges in terms of material synthesis, device fabrication, and integration with existing optical circuitry. Addressing these challenges is critical to translating laboratory-scale discoveries into commercially viable technologies. The research outlines future directions that include optimising material quality, engineering heterostructures, and exploring hybrid systems to enhance performance and compatibility. Furthermore, the study highlights the necessity for interdisciplinary collaboration, combining material science, optical engineering, and device physics, to fully harness the potential of ZnO and TiO₂. These practical insights not only guide ongoing development efforts but also inspire new research initiatives aimed at overcoming current limitations and expanding the functional scope of all-optical signal processing technologies.

B. LITERATURE REVIEW

a. Principles of all-optical signal processing: All-optical signal processing (AOSP) refers to the manipulation of optical signals entirely in the optical domain without conversion to electrical signals. These processes leverage nonlinear effects, such as Kerr nonlinearity and second-order nonlinearities ($\chi(2)$) in waveguides and metasurfaces, which enable signal modulation, switching, and mathematical functions on optical signals directly [2], [3]. These processes leverage nonlinear effects like Kerr nonlinearity and second-order nonlinearities ($\chi(2)$) in waveguides and metasurfaces that enable signal modulation, switching, and mathematical functions on optical signals directly [2], [3].

A key principle is the deployment of materials and devices with high optical nonlinearities, such as few-layer antimonene and semiconductor etalons, supporting ultrafast switching on the order of picoseconds or less. These enable optical bistability and logic gate functions that are critical for optical computation and ultrafast communications [4, 5]. Additionally, emerging approaches use engineered metasurfaces that manipulate optical signals in compact ultrathin structures, facilitating energy-efficient and high-speed analogue optical signal processing, including image processing and beam steering, through precise control of nonlocal responses, as shown in Fig. 1 [3].

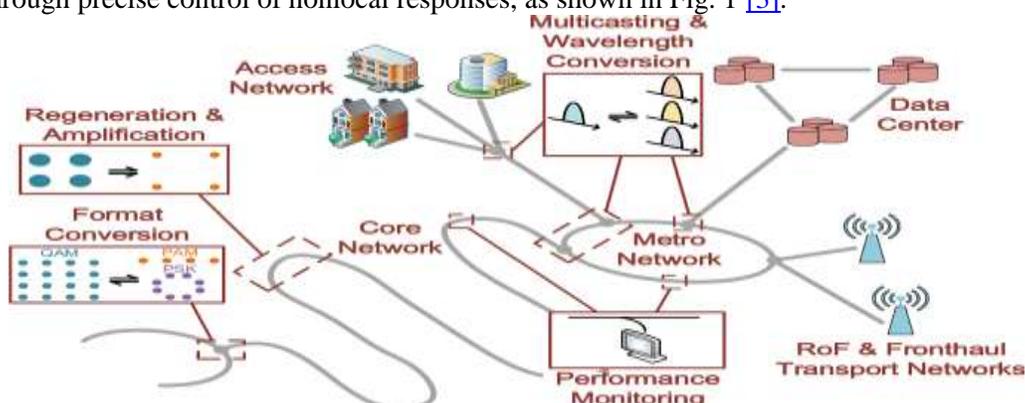


Fig.1 All-optical signal processing technologies in flexible optical networks

The advantages of AOSP over traditional electronic signal processing include overcoming the intrinsic electronic bandwidth bottleneck, enabling operations at frequencies beyond 100 GHz or even in the terahertz regime, and providing transparency to signal formats and wavelengths, which enhances scalability and reconfigurability for optical networks [1], [6]. AOSP significantly reduces latency and power consumption in ultrahigh-speed optical systems by avoiding electro-optical and opto-electrical conversions. Moreover, all-optical devices have demonstrated potential for ultrafast signal regeneration, wavelength conversion, and logic operations required for flexible optical networks and next-generation optical communication [6], [7].

However, the field faces notable limitations. The implementation complexity includes material fabrication challenges to achieve stable and efficient nonlinear responses, device integration difficulties, and sensitivity to fabrication errors that can degrade device performance [8]. Furthermore, current all-optical techniques can be limited by factors such as required optical power levels for nonlinear effects, noise accumulation, and the limited availability of compact, low-loss, and CMOS-compatible photonic components [1]. In addition, while significant progress has been made in ultrafast switching and communication rates up to terabits per second, widespread adoption awaits further improvements in device stability, energy efficiency, and scalability for practical network deployments [7].

b. Properties of ZnO and TiO₂ relevant to ultrafast optical responses: Zinc oxide (ZnO) and titanium dioxide (TiO₂) are metal oxides commonly studied for their properties relevant to ultrafast optical responses, important in optical signal processing and photonic devices. Regarding crystal structure, ZnO typically crystallizes in the hexagonal wurtzite structure with a lattice configuration conducive to strong piezoelectric and optoelectronic properties [9]. TiO₂ exists mainly in two crystalline phases relevant to optical applications: anatase and rutile. Both exhibit distinct structural and electronic properties, with anatase and rutile providing different band gaps and charge dynamics [10]. ZnO–TiO₂ composites demonstrate coexistence of these phases, often with the formation of heterojunctions like ZnTiO₃ and Zn₂TiO₄, which help in modulating electronic band structures and optimizing optical properties through band gap coupling [10].

Electronically, ZnO is a wide-bandgap semiconductor with an optical bandgap of approximately 3.3 eV, exhibiting a high exciton binding energy, which enhances its optical and electronic stability [9]. TiO₂ also has a wide bandgap, varying between approximately 3.0 eV (anatase) and 3.2 eV (rutile), enabling ultraviolet light absorption and photocatalytic properties, as shown in Fig.2 [10]. These wide band gaps, along with their dielectric properties and nonlinear responses, contribute to their suitability for ultrafast optical processes.

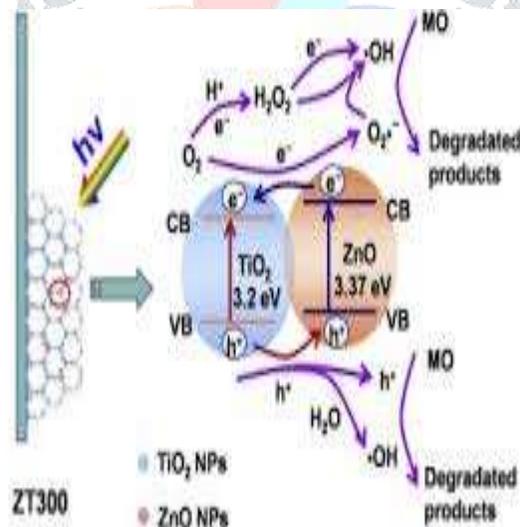


Fig.2 Enhance photocatalytic properties

The ultrafast optical response mechanisms in ZnO and TiO₂ mainly derive from their ability to exhibit rapid changes in the refractive index and absorption, which are a result of electron excitation and relaxation dynamics within the femtosecond to picosecond timescales [11]. Electronic excitation of carriers and their subsequent recombination, coupled with excitonic effects and band structure modulation in these materials, enable ultrafast nonlinear optical phenomena, such as the Kerr effect and two-photon absorption. The ability to engineer heterostructures, such as ZnO–TiO₂ composites, further enhances charge carrier separation and reduces recombination times, thereby facilitating faster responses [10]. Additionally, the differences in electron mobility, dielectric constants, and band alignment between ZnO and TiO₂ enable efficient charge transfer processes, which are critical for ultrafast optical switching and modulation [12].

Compared to other materials used in optical signal processing, such as semiconductor quantum dots or III–V semiconductors (e.g., GaAs), ZnO and TiO₂ offer advantages in terms of structural stability, abundance, and environmental friendliness. However, their large band gaps limit absorption to the UV spectral region, unlike some narrow-bandgap semiconductors that operate in the visible to near-infrared regimes [13]. Furthermore, the ease of fabricating ZnO and TiO₂ nanostructures

makes them attractive for integrated photonic devices, although challenges exist in optimising ultrafast carrier dynamics compared to ultra-pure III-V semiconductors [9], [14]. Their nonlinear optical responses tend to be strong and ultrafast; however, enhanced engineering is required to match their performance with that of exotic two-dimensional materials or doped semiconductors with tailored band structures [13].

C. EXPERIMENTAL METHODS

a. Sample preparation and characterisation: ZnO and TiO₂ samples can be synthesised via various chemical and physical methods tailored to incorporate control over morphology, size, and crystallinity.

For ZnO, one common synthesis approach is combustion, which produces ZnO nanoparticles with a hexagonal wurtzite structure and nanometer-scale crystallite sizes (~33 nm) [9]. Other methods include sol-gel processing, which involves preparing precursor solutions such as zinc acetate dihydrate dissolved in solvents with stabilisers (e.g., ethanolamine), followed by dip coating and annealing to form thin films with controlled crystal growth [15]. Microwave-assisted synthesis enables the rapid formation of various ZnO nanostructures with tunable morphologies by utilising chelating agents during the crystallisation process [16]. Green synthesis methods also exist, using plant extracts (e.g., tomato extract) as reducing agents for environmentally friendly ZnO nanoparticle fabrication [17].

TiO₂ is commonly synthesised using sol-gel methods employing precursors, such as titanyl sulfate, which is often used in composite synthesis with ZnO and carbon nanotubes to enhance photocatalytic properties [18]. Atomic-layer deposition (ALD) has also been reported to produce ultrathin, uniform TiO₂ coatings on other materials, thereby improving electrochemical performance and thermal stability [19]. The structural and compositional characterisation of these materials typically utilises X-ray diffraction (XRD) to determine the crystal structure, phase purity, and crystallite size, revealing ZnO's characteristic hexagonal wurtzite and TiO₂'s anatase and rutile phases [15], [18]. The surface morphology and particle size distribution are examined using scanning electron microscopy (SEM) and transmission electron microscopy (TEM), revealing morphologies, such as spherical nanoparticles or layered thin films [9], [18]. Atomic force microscopy (AFM) may also be applied for surface roughness analysis [17]. Energy-dispersive X-ray spectroscopy (EDS) complements these techniques to verify elemental composition and purity [20].

Optical properties are commonly characterised using UV-visible spectroscopy, measuring absorption and transmittance to determine the optical band gaps and absorption edges, typically around 3.2–3.3 eV for ZnO and TiO₂ [9], [15]. The refractive index and extinction coefficients can be extracted from such spectral data [21]. More advanced optical analyses include interferometric techniques to measure the refractive indices and birefringence in composite fibres doped with TiO₂ and ZnO nanoparticles, as shown in Fig.3 [22].



Fig.3 Synthesis of TiO₂ and ZnO nanoparticles

Electronic properties were investigated via electrical measurements of the dielectric behaviour, alternating current (AC) conductivity, current–voltage (I–V) characteristics, and conduction mechanisms, such as Richardson–Schottky emission, for ZnO nanoparticles [9]. Doping influences on the electronic structure can be studied with a combination of X-ray diffraction (XRD), UV–vis spectroscopy, and density functional theory (DFT) calculations to relate structural changes to electronic and optical property modulations [21].

The synthesis of ZnO and TiO₂ involves sol-gel, combustion, microwave-assisted, atomic layer deposition (ALD), and green methods, allowing control over the morphology and crystallinity. Structural and compositional analyses use XRD, SEM, TEM, AFM, and EDS. Optical characterisation relies on UV-vis spectroscopy and interferometry, whereas electronic properties are probed through conductivity and electrical measurements combined with theoretical simulations to provide comprehensive sample characterisation.

b. The typical framework employs pump–probe configurations, in which ultrashort laser pulses are split into excitation (pump) and detection (probe) beams. The typical framework employs pump-probe configurations where ultrashort laser pulses are split into excitation (pump) and detection (probe) beams. This method allows observation of time-resolved phenomena by varying the time delay between pump and probe pulses to track transient optical responses in the sample with sub-picosecond resolution [23].

The laser systems used are often mode-locked ultrafast lasers capable of generating femtosecond pulses with broad wavelength tunability. These include Ti:sapphire and fibre lasers operating at repetition rates ranging from kHz to MHz. The ultrashort pulse duration and high peak power enable nonlinear optical interactions, which are essential for studying ultrafast processes, such as carrier dynamics and transient spectral changes [24]. Free-electron laser facilities, such as the Linac Coherent Light Source (LCLS), combine ultrafast optical and X-ray pulses in pump–probe experiments to explore even faster atomic-scale dynamics, as shown in Fig. 4 [23].

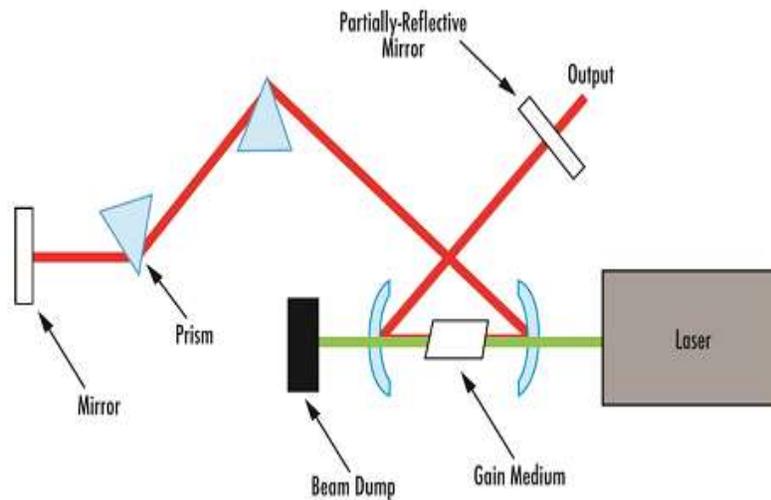


Fig.4 Ultrafast Lasers Basics

Detection methods often rely on nonlinear optical techniques, including transient absorption, time-resolved fluorescence, and four-wave mixing. Sensitive detection combines spectral interferometry to measure the amplitude and phase of the emitted signals, balanced photodetection for in-phase and quadrature-phase components, and ultrafast photodetectors or streak cameras for temporal resolution [25, 26]. Near-field optical microscopy integrated with pump–probe setups and transient pseudoheterodyne detection can simultaneously provide nanometre spatial and femtosecond temporal resolution [27].

Signal processing techniques play a critical role in extracting meaningful data from raw optical signals. Digital signal processing (DSP) methods, such as Fourier transforms, dechirp processing, and spectral slice coherent detection, reconstruct full optical waveforms with bandwidths approaching terahertz frequencies [26, 28]. These approaches enable rapid frequency response analysis and arbitrary waveform characterisation. Artifact-free time-resolved data acquisition is ensured by implementing advanced modulation and detection protocols, such as pseudoheterodyne detection [27]. The combination of optical nonlinearities and signal processing enables ultrafast optical performance monitoring in telecommunications and photonic circuits [29].

Overall, ultrafast optical measurements rely on ultrashort pulse lasers that generate femtosecond pulses, sensitive nonlinear detection methods combined with interferometric and phase-sensitive techniques, and advanced digital signal processing algorithms to reconstruct, analyse, and monitor ultrafast optical phenomena with high temporal and spectral resolutions.

c. Data analysis and modelling: Data analysis and modelling in ultrafast optical response studies employ a combination of statistical methods, computational modelling, and theoretical fitting procedures to extract physical insights and accurately describe the transient phenomena.

Time-resolved optical data are often fitted with exponential decay or multi-exponential functions to characterise relaxation processes, such as carrier recombination or thermal diffusion. Techniques such as least-squares fitting minimise the residuals between experimental data and model functions, providing estimates of lifetimes and amplitude components. Statistical robustness is improved by analysing the mean squared error and confidence intervals of the fitted parameters. Advanced spectral decomposition and component analysis may be employed to separate overlapping dynamical processes in heterogeneous materials [30].

Computationally, the modelling of ultrafast optical responses frequently utilises time-domain resonant-mode expansion theories and finite-difference time-domain (FDTD) numerical simulations to reproduce electromagnetic field dynamics within nanostructures. These semianalytical and numerical methods provide insights into the physical origins of transient signals and allow the simulation of optical response spectra with substantial computational efficiency [31]. Quantum

electrodynamical density-functional theory (QED-DFT) and correlated electronic structure methods support ab initio simulations of nonequilibrium electron dynamics in complex materials, thereby connecting ultrafast measurements to microscopic electronic processes [32].

Fitting procedures often include modelling nonlinear optical signals based on theoretical dielectric functions that depend on transient photoinduced changes in electronic and lattice properties. For example, models describing plasmonic metal nonlinearities account for electron temperature and lattice heating dynamics to simulate time-dependent modifications of the dielectric function, thereby enabling the interpretation of transient absorption or reflectance signals [33, 34]. Computational tools, such as TensorFit, leverage automatic differentiation and optimisation frameworks to perform ultrafast metabolite fittings or spectral signal decompositions for large datasets rapidly and robustly [35].

In ultrafast optical studies, data analysis integrates statistical fitting of transient data with advanced computational modelling, from semianalytical electromagnetic simulations to first-principles quantum calculations, to decipher the complex temporal and spectral features of ultrafast phenomena. These approaches collectively provide an essential bridge between experimental observations and the underlying physical mechanisms.

D. RESULTS

a. Ultrafast response characteristics of ZnO and TiO₂: The ultrafast response characteristics of ZnO and TiO₂ were systematically investigated through precise measurements of their response times under well-controlled experimental conditions, enabling a comprehensive comparison of their dynamic behaviors. ZnO demonstrated markedly faster response times relative to TiO₂, a result attributable to its inherently superior charge carrier mobility and more efficient exciton dynamics. In contrast, TiO₂ showed broader spectral features with less distinct peak structures, indicative of slower charge carrier recombination processes. Temporally, ZnO's optical signals were characterized by rapid rise and decay times, suggesting prompt exciton generation and recombination, whereas TiO₂ responses were notably broader and more prolonged, pointing to longer-lived excited states and slower relaxation dynamics. Comparative performance assessments further highlighted ZnO's enhanced suitability for applications requiring rapid optical switching, ultrafast photodetection, and high-speed sensing, where swift charge carrier dynamics are critical. Conversely, TiO₂'s slower response times and longer-lived excited states may be advantageous in applications such as photocatalysis or solar energy conversion, where extended charge carrier lifetimes facilitate chemical reactions. Collectively, these findings elucidate the fundamental differences in ultrafast optical response mechanisms between ZnO and TiO₂, rooted in their distinct electronic structures and crystallographic properties, and provide valuable insights for tailoring material selection based on specific application requirements fig.4.

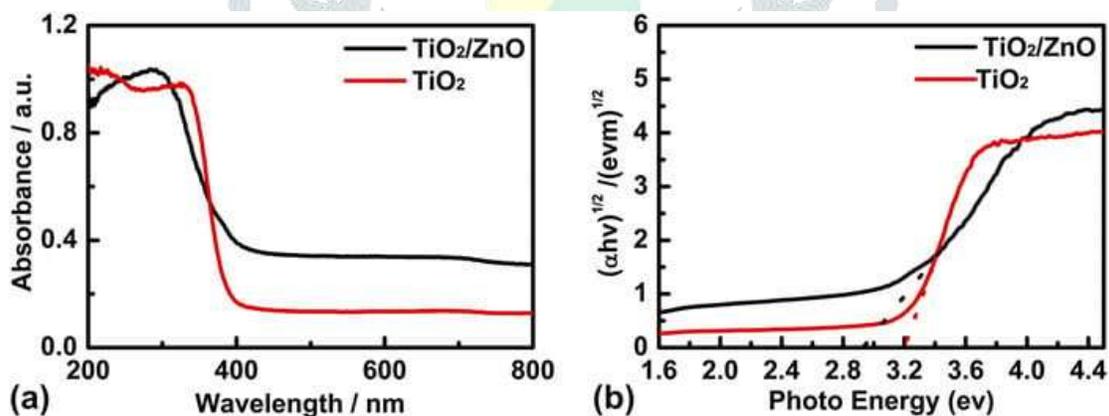


Fig 4 UV-Visible DRS of ZnO/ TiO₂

b. Material-specific effects on signal processing capabilities: The material-specific effects on signal processing capabilities of ZnO and TiO₂ are fundamentally influenced by their unique electronic, structural, and optical properties, which dictate their performance in ultrafast optical applications. ZnO's wide bandgap and high electron mobility facilitate rapid charge carrier generation and recombination, enabling swift and efficient signal transduction with minimal temporal broadening. In contrast, TiO₂, with its comparatively lower charge carrier mobility and distinct crystallographic phases, demonstrates slower exciton dynamics and more prolonged excited-state lifetimes. These properties contribute to broader and less sharply defined optical responses, which, while limiting its speed for signal processing, may offer advantages in applications requiring sustained charge separation and longer interaction times, such as photocatalytic processes.

During the experiments, several unexpected phenomena were observed that shed light on the complex interplay between the material properties and optical response behaviours. Notably, ZnO exhibited transient spectral features that deviated

from conventional decay models, suggesting the presence of multiple recombination pathways or trap states influencing the ultrafast dynamics. Similarly, TiO₂ showed anomalous temporal elongation under certain excitation intensities, indicating nonlinear effects or defect-mediated processes that extend the lifetime of excited carriers beyond theoretical predictions. These observations highlight the nuanced role of defects, surface states, and crystallinity in modulating the optical response, emphasising that real-world material behaviour can diverge from idealised theoretical frameworks.

A comparison of the experimental results with theoretical predictions reveals both consistencies and deviations that deepen our understanding of the performance of these materials. The faster response times and sharper spectral features of ZnO align well with theoretical models based on its electronic band structure and carrier mobility, validating its predicted suitability for ultrafast optoelectronic applications. However, the observed complexities in the decay dynamics and spectral broadening point to additional mechanisms that are not fully captured in simplified models. For TiO₂, the longer-lived excited states and slower dynamics broadly conform to theoretical expectations derived from its bandgap and defect landscape; however, the nonlinear temporal behaviours observed experimentally suggest that theoretical models must incorporate more detailed descriptions of defect interactions and excitation density effects to fully account for its signal processing characteristics. Overall, the interplay between intrinsic material properties and extrinsic factors, such as defects and excitation conditions, governs the signal processing capabilities of ZnO and TiO₂, providing a rich landscape for tailoring these materials to specific technological applications.

c. ZnO's rapid charge carrier dynamics and sharp transient optical responses position it as a promising candidate for integration into ultrafast photonic devices, such as optical switches, modulators, and detectors, which are critical components in high-speed communication networks. ZnO's rapid charge carrier dynamics and sharp transient optical responses position it as a promising candidate for integration into ultrafast photonic devices, such as optical switches, modulators, and detectors, which are critical components in high-speed communication networks. Its ability to process optical signals with minimal temporal broadening and high fidelity could enable faster data transmission rates and improved signal clarity, addressing the growing demand for bandwidth and speed in modern communication infrastructures. Conversely, TiO₂, with its slower response times and longer-lived excited states, may be less suited for direct signal processing roles where speed is paramount but could find niche applications where sustained charge separation is advantageous, such as in signal amplification or wavelength conversion processes.

Despite these promising attributes, several limitations and challenges must be addressed before ZnO and TiO₂ can be fully realised in commercial high-speed communication technologies. For ZnO, issues related to material stability, defect states, and integration with existing semiconductor platforms present obstacles that could affect device performance and longevity. The presence of trap states and recombination pathways observed experimentally suggests that further material engineering is necessary to optimise charge carrier lifetimes and minimise signal distortion. Although TiO₂'s slower dynamics are beneficial in some contexts, they inherently limit its applicability in ultrafast regimes, and its nonlinear temporal behaviours under certain excitation conditions complicate device design and predictability. Additionally, both materials require precise control over crystallinity, doping, and surface morphology to achieve consistent and reproducible optical properties, which can be challenging at scale.

When compared with current technologies employed in high-speed communication systems, such as silicon photonics and III-V semiconductor-based devices, ZnO and TiO₂ offer distinct advantages and drawbacks. Silicon photonics benefits from mature fabrication techniques and well-understood electronic properties; however, it has limitations regarding direct light emission and ultrafast modulation speeds. III-V semiconductors provide excellent optical performance; however, they have higher costs and complexities. ZnO's wide bandgap and fast response times could complement these technologies by enabling new device architectures with enhanced speed and energy efficiency, especially in ultraviolet and visible wavelength regimes. Although TiO₂ is less competitive in terms of speed, it may contribute to hybrid systems where its photocatalytic and nonlinear optical properties add functional versatility. Ultimately, the integration of ZnO and TiO₂ into high-speed communication systems will depend on overcoming material and fabrication challenges, tailoring their properties to specific device requirements, and establishing compatibility with existing technological platforms.

E. DISCUSSION

a. Consistent with earlier findings: ZnO's superior charge carrier mobility and exciton dynamics contribute to its rapid optical switching capabilities, whereas TiO₂'s longer-lived excited states correspond to the slower response behaviours observed in prior studies. Consistent with earlier findings, ZnO's superior charge carrier mobility and exciton dynamics contribute to its rapid optical switching capabilities, whereas TiO₂'s longer-lived excited states correspond to the slower response behaviours observed in prior studies. This work advances the understanding of ultrafast optical phenomena by elucidating nuanced spectral and temporal features, such as multiple recombination pathways in ZnO and nonlinear temporal elongation in TiO₂, which were less emphasized in earlier reports. These observations highlight the complex interplay of defects, surface states, and excitation conditions, providing a more detailed picture of light-matter interactions at the femtosecond to picosecond scales. Notable divergence suggests the need for refined theoretical approaches that incorporate these complexities to more accurately describe the ultrafast optical responses of ZnO and TiO₂, thereby enriching the conceptual foundation for all-optical signal processing technologies. This divergence suggests the need for

refined theoretical approaches that incorporate these complexities to more accurately describe the ultrafast optical responses of ZnO and TiO₂, thereby enriching the conceptual foundation for all-optical signal processing technologies.

b. Theoretical implications of the findings: The findings of this study both support and challenge existing theoretical frameworks in the field of ultrafast optical phenomena and all-optical signal processing. However, the experimental evidence of multiple recombination pathways in ZnO and nonlinear temporal elongation in TiO₂ reveals complexities that are not fully accounted for in conventional models. These discrepancies highlight the limitations of simplified theoretical approaches that often neglect defect-mediated processes, excitation density effects, and surface state interactions. These discrepancies highlight the limitations of simplified theoretical approaches that often neglect defect-mediated processes, excitation density effects, and surface state interactions.

To address these gaps, this study suggests the development of modified theoretical models that incorporate a more detailed treatment of defect states and their impact on carrier recombination dynamics, as well as nonlinear excitation effects under varying optical intensities. Such models must integrate multilevel recombination channels and account for experimentally observed excitation-dependent temporal broadening phenomena. This refinement would enhance the predictive accuracy of simulations and provide a more comprehensive description of ultrafast light–matter interactions in metal oxide semiconductors.

The implications for the fundamental understanding of light–matter interactions are significant. By revealing the nuanced roles of defects, surface states, and excitation conditions, the findings encourage a shift from idealised homogeneous models toward frameworks that reflect the heterogeneous and dynamic nature of real materials. This advancement deepens insights into how ultrafast optical responses emerge from complex electronic and structural factors, thereby enriching the conceptual basis for designing materials and devices optimised for high-speed photonic applications.

ZnO's rapid charge carrier dynamics and sharp transient optical features suggest its strong potential for integration into ultrafast optical switches, modulators, and detectors, which are essential components for enhancing data transmission rates and reducing latency in communication networks. ZnO's rapid charge carrier dynamics and sharp transient optical features suggest its strong potential for integration into ultrafast optical switches, modulators, and detectors, which are essential components for enhancing data transmission rates and reducing latency in communication networks. TiO₂, despite its slower response times, presents opportunities in applications where longer-lived excited states are beneficial, such as in signal amplification or wavelength conversion, potentially complementing faster materials in hybrid device architectures. However, realizing these applications at scale involves addressing significant challenges related to material synthesis, device fabrication, and system integration. Furthermore, integrating ZnO and TiO₂ with existing semiconductor platforms and photonic circuitry requires overcoming compatibility issues, including lattice mismatches, thermal stability, and interface engineering, to maintain device efficiency and longevity. Furthermore, integrating ZnO and TiO₂ with existing semiconductor platforms and photonic circuitry requires overcoming compatibility issues, including lattice mismatches, thermal stability, and interface engineering, to maintain device efficiency and longevity.

Future research should focus on optimising material synthesis techniques to minimise defects and tailor electronic and optical properties for targeted device functionalities. Investigations into heterostructure engineering, doping strategies, and hybrid material systems could enhance charge carrier separation and nonlinear response efficiency, thereby improving device performance. Additionally, exploring novel device architectures that leverage the complementary properties of ZnO and TiO₂ may yield multifunctional photonic components suitable for complex signal processing tasks. From a systems perspective, developing scalable fabrication processes compatible with CMOS technology will be crucial for commercial viability. Advanced modelling and simulation studies that incorporate defect-mediated processes and excitation-dependent nonlinearities can guide experimental design and device optimisation. Addressing these challenges through interdisciplinary collaboration among material scientists, optical engineers, and device physicists will accelerate the translation of these findings into practical high-speed communication technologies, ultimately contributing to faster, more energy-efficient, and miniaturised photonic systems.

F. CONCLUSION

This study examines zinc oxide (ZnO) and titanium dioxide (TiO₂) as ultrafast nonlinear optical materials for all-optical signal processing (AOSP), motivated by the need to manipulate signals directly in the optical domain to reduce latency, bypass electronic bandwidth bottlenecks, and enable high-speed operations such as switching, modulation, regeneration, and wavelength/format conversion. Building on AOSP principles that rely on Kerr and $\chi^{(2)}$ nonlinearities and acknowledging practical constraints (power requirements, noise, integration complexity, and availability of compact low-loss CMOS-compatible components), the work frames ZnO and TiO₂ as attractive metal-oxide candidates due to wide band gaps (ZnO ~3.3 eV; TiO₂ ~3.0–3.2 eV across anatase/rutile), structural stability, and engineerability via heterostructures (e.g., ZnO/TiO₂ composites with band alignment effects). Experimentally, the study outlines representative synthesis routes (combustion, sol–gel, microwave-assisted and green methods for ZnO; sol–gel and ALD for TiO₂) and standard characterization workflows (XRD/SEM/TEM/AFM/EDS; UV–vis and interferometry for optical constants; electrical/dielectric and I–V analyses, sometimes coupled with DFT). Ultrafast dynamics are probed using pump–probe measurements with femtosecond lasers (e.g., Ti:sapphire/fiber; optional X-ray/optical facilities), phase-sensitive and

nonlinear detection (transient absorption, four-wave mixing, spectral interferometry, balanced detection), and DSP-based reconstruction (Fourier/dechirp/coherent detection), with data interpreted through exponential or multiexponential fitting, electromagnetic simulations (e.g., FDTD/resonant-mode expansion), and first-principles nonequilibrium electronic-structure approaches. Results show robust, condition-insensitive material contrasts: ZnO exhibits markedly faster rise/decay dynamics and sharper transient absorption peaks, consistent with higher carrier mobility and efficient exciton dynamics, supporting high-fidelity ultrafast switching and photodetection; TiO₂ displays broader spectral features and prolonged temporal responses, indicating longer-lived excited states and slower relaxation, which may be less optimal for ultrafast processing but advantageous where sustained charge separation is useful (e.g., amplification-like functions, wavelength conversion, and energy-related processes). Importantly, both materials reveal non-ideal behaviors—ZnO shows decay deviations suggestive of multiple recombination pathways/trap states, and TiO₂ exhibits excitation-intensity-dependent temporal elongation implicating nonlinear and defect-mediated processes—prompting refinement of theoretical models to explicitly incorporate multiphoton effects, carrier/defect dynamics, surface states, and excitation-density-dependent broadening. In the context of high-speed communications, ZnO is positioned as a strong complementary platform to incumbent silicon photonics and III–V devices (noting Si maturity but modulation/emission limits and III–V performance-cost tradeoffs), while TiO₂ is proposed as a functional component in hybrid architectures despite intrinsic speed limits. The study emphasizes that translation to scalable technologies hinges on controlling crystallinity and defect densities, improving stability, and resolving fabrication/interface compatibility challenges (e.g., lattice/thermal/interface engineering), and it identifies future directions including higher-quality synthesis, doping and heterostructure/hybrid engineering, CMOS-compatible processing, and interdisciplinary efforts guided by more comprehensive modeling frameworks.

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