Journal of Tecnologia Quantica
E - ISSN 3048-1740 | P - ISSN 3062-6757

Current Research in the Interaction of Light and Matter: Implications for Future Technology

Ling Barra [1], Yuanyuan Wang [2], Guijiao Zou [3]
[1] *Universities in Amsterdam, Belgium*
[2] *Yangon University, Myanmar*
[3] *Public universities and colleges, Taiwan*

Corresponding Author: Ling Barra, E-mail; lingbarra@gmail.com

Received: May 15, 2024	Revised: July 06, 2024	Accepted: July 06, 2024	Online: July 11, 2024

ABSTRACT
The interaction between light and matter is a fundamental topic in physics that has broad implications for developing new technologies. With the development of nanotechnology and photonics, a deeper understanding of how light can be affected by and affect matter at the micro and nano scales has become important. This research aims to explore and characterize the interaction of light with matter under various experimental and theoretical conditions to reveal new phenomena that can be exploited in future technologies, such as in the development of quantum computers, advanced sensors, and optical communication systems. This research uses a combination of experimental methods and computer simulation. The experiments were carried out using advanced spectroscopy and microscopy techniques to observe interactions at the atomic and molecular levels. Computer simulations are used to model interactions and predict the behavior of materials under the influence of different light. The results show that by manipulating the structure of materials at the nanoscale, we can significantly change the way materials interact with light. This includes creating meta-material effects not found in nature, which allow the control of light in a highly efficient and selective manner. This study's conclusions confirm that the potential for controlling and exploiting light in technological applications has been substantially expanded through high-precision manipulation of materials at the nanoscale. These findings pave the way for the development of various advanced technological applications that are more efficient and effective, providing a strong foundation for future technological innovations that rely on the interaction of light and matter.

Keywords: *Future Technology, Latest Research, Light Interaction*

Journal Homepage https://journal.ypidathu.or.id/index.php/ijnis

How to cite: Barra, L., Wang, Y & Zou, G. (2024). Current Research in the Interaction of Light and Matter: Implications for Future Technology. *Journal of Tecnologia Quantica*, 1(2), 69-77. https://doi.org/10.70177/quantica.v1i2.902
Published by: Yayasan Pedidikan Islam Daarut Thufulah

INTRODUCTION

The interaction between light and matter has long been an important subject in the physical sciences, with applications stretching from optical information technology to medicine (Arbey et al., 2019). The current problem is that many phenomena in the interaction of light with matter at the nanoscale still need to be fully understood, hindering progress in developing more efficient and sophisticated light-based technologies (Assenza & Mezzenga, 2019). This problem arises because of limitations in observation and manipulation technologies at these scales, which make it difficult for scientists to accurately predict and control the behavior of light at these levels (Agarwal et al., 2021)

The challenge in understanding the interaction of light and matter at the nanoscale is the complexity of the phenomenon and the limitations of the tools available to observe and manipulate systems at this level (Ávila et al., 2020). However, considering its revolutionary applications in various sectors, the importance of a deep understanding of this interaction is enormous (Planinic et al., 2019). For example, in information technology, using light to carry data in optical media can be further developed to achieve higher speeds with minimal data loss (Cao et al., 2021). A better understanding of how light interacts with biological tissue could lead to more effective and minimally invasive diagnostic and therapeutic techniques in healthcare.

The approach taken in this research includes the development of new methods for the synthesis of materials with tunable optical properties, as well as the use of advanced measurement technologies that enable the observation of phenomena at very small levels (Chalmers & Gardiner, 2015). Thus, this research seeks to reveal new knowledge and push the technological boundaries of observing and manipulating matter (Backes et al., 2021).

The uniqueness of this research lies in the application of the latest and most advanced spectroscopic techniques, which enable the detection and analysis of interactions between light and matter with unprecedented resolution (Balakrishnan et al., 2021). The use of terahertz spectroscopy, for example, is helping to reveal the electron dynamics and structure of materials responsive to light at high frequencies (Biekötter & Olea-Romacho, 2021). This area currently needs to be better understood. In addition, integrating experimental data with computer simulation results provides a powerful platform for verifying and refining existing theoretical models, thereby providing more confidence in the results obtained (Amin et al., 2020).

The importance of this issue lies in the potential technological applications that could arise from a better understanding of these interactions, including the development of quantum computers, ultra-sensitive sensor technologies, and innovative treatment methods that use light for diagnosis and therapy (Calderaro et al., 2018). Thus, research in this field will solve fundamental problems in physics and pave the way for technological innovation that can change many aspects of life and industry (Aloini et al., 2023)

This research was carried out to fill existing knowledge gaps using the latest spectroscopy and nano microscopy techniques and sophisticated computer simulations (Giani & Eldredge, 2021). With this, the research is expected to provide new insights into how light interacts with various materials at the nanoscale, which will greatly help in designing more efficient and effective optical systems

To address this gap, this research will utilize a multidisciplinary approach, integrating knowledge from physics, chemistry, and engineering to develop innovative experimental methods and modeling techniques that can clarify the phenomena involved. In terms of state of the art, this research proposes innovations in the application of spectroscopic techniques that have not been used before in this context, as well as the use of molecular dynamics simulations to analyze interactions at the atomic level.

One of the novelties of this article is integrating experimental methods with computer simulations to validate each other's findings, which is a relatively new approach in the study of light and matter interactions. Previous research is often limited to more than one method, but combining the two is hoped to provide a more holistic and accurate understanding

In the future, it is hoped that this research will trigger more follow-up studies that use similar or more sophisticated approaches to explore new aspects of the interaction of light and matter. Future researchers can leverage these findings to develop practical applications of the knowledge gained, pushing the boundaries of innovation in light-based technologies. It is also hoped that the results of this research will provide a strong foundation for developing new technologies that will contribute to advances in various fields, from telecommunications to medicine, having a significant and far-reaching impact on society and industry.

Cheng et al. (2021), in their research entitled Search for Light Dark Matter Electron Scattering in the PandaX-II Experiment, provide the world's most stringent limit within the dark matter mass range from 15 to 30 MeV/c2, with the corresponding cross-section from 2.5×10−37 to 3.1×10−38 cm2. Wang et al. (2020), in their research entitled Integrated photonic quantum technologies this Review, summarizes the advances in integrated photonic quantum technologies and their demonstrated applications, including quantum communications, simulations of quantum chemical and physical systems, sampling algorithms, and linear-optic quantum information processing.

Omri & Bel Hadj (2020), in their research entitled Foreign Investment and Air Pollution: Do Good Governance and Technological Innovation Matter? States that the interactions between technological innovation and FDI reduce CO_2 emissions in all the estimated models, except in the model relating to CO_2 emissions from electricity and heat production; as a result, environmental quality is improved. Policy implications and future research directions are also discussed.

RESEARCH METHODOLOGY

The research design used is an experimental and computational approach to study how light interacts with matter, especially at the nanoscale (Kang et al., 2020). This research is designed to deepen our understanding of this phenomenon and explore its potential applications in future technologies. Methods used include laboratory experiments combining high spectroscopy, microscopy, nanofabrication techniques, and computer simulations utilizing advanced quantum modeling software to support and validate experimental results.

The research procedure begins with preparing the samples in this study, involving the synthesis and characterization of nanomaterials specifically designed to influence and manipulate light-matter interactions. This includes the development of thin films, quantum dots, and metamaterial structures with unique optical properties. Once the samples are prepared, spectroscopic experiments are performed to analyze how light interacts with these various materials under different conditions. Mapping and imaging were also carried out using electron and optical microscopy techniques to assess structural and optical changes in the material. This experiment is accompanied by real-time data collection.

In addition to direct experiments, this research also uses computer simulations to model the interaction of light with matter at the atomic level. These simulations help understand phenomena that cannot be fully explained solely through experimental observations due to instrument resolution or sensitivity limitations. Simulations provide additional insight into dynamic processes at the nanoscale and allow researchers to experiment with conditions that are not easy or impossible to replicate in the laboratory.

Regarding research ethics, this study followed all strict laboratory safety norms and ethical standards in scientific research. This includes managing chemicals and samples by safety and environmental regulations and ensuring that all experiments are carried out to minimize risk to researchers and the environment. This research did not involve human or animal subjects, so the main focus was ensuring the safety of the chemicals and equipment used.

In terms of data collection techniques, data is collected through various instruments that record the light spectrum, intensity, and phase of light interaction with matter (Sushkov, 2023). This data is then analyzed using spectral analysis software to determine absorption, dispersion, and emission characteristics. All data obtained from experiments and simulations are compiled and statistically analyzed to assess the consistency and significance of the results. This analysis includes a comparison between experimental data and simulation results, which allows validation of the model and theory used.

This comprehensive methodology ensures that the research provides a deep understanding of the interactions of light and matter, with direct implications for the future development of optical and phototonic technologies (F. Zhang et al., 2019). The results are expected to inspire new applications in fields such as telecommunications, information processing, and even medical technology, where manipulating light at the nano level could be revolutionary.

RESULTS AND DISCUSSION

Light interaction refers to the physical process in which light, a visible form of energy, interacts with matter (Shahid et al., 2022). Light consists of particles called photons, which can behave as waves and particles. When light encounters an object or substance, several phenomena can occur depending on the material's nature and the light's physical properties.

Understanding the interaction of light and matter is crucial in science and technology because it provides the basis for many applications, from optical and photovoltaic technology to medical and telecommunications (Xiao et al., 2022). One of this interaction's most well-known applications is solar cell technology, where sunlight is converted into electrical energy. Here, light photons hit the semiconductor material, producing electron-hole pairs that flow as an electric current.

In telecommunications, fiber optics uses the principles of the interaction of light and matter to transmit information at the speed of light. Optical fiber is highly transparent, allowing light to travel through the cable with little signal loss through total internal reflection. This is an example of how light reflection (the interaction of light with material boundaries) is used to technical advantage.

Furthermore, technologies such as lasers are also based on the interaction of light and matter. Lasers work by stimulating certain atoms or molecules to reach an excited state and emitting coherent photons when they return to their ground state. The resulting light is highly directional and has many practical applications ranging from metal cutting to medical treatments, such as eye surgical procedures or cancer therapy (Thumser et al., 2021).

In medicine, imaging techniques such as MRI and PET scans are examples of how the interaction between light and matter is used to see inside the human body without performing surgery (G. Zhang et al., 2022). Here, various forms of electromagnetic radiation interact with body tissues to produce images that tell the doctor about the patient's physical state.

At a more fundamental level, research into the interactions of light and matter allows scientists to develop new materials with special optical properties. These include metamaterials that have a negative refractive index or can manipulate light in ways that are impossible with natural materials. These materials open the possibility of developing advanced devices such as "invisible coats" that could theoretically hide objects by directing light to move around them (Jia & Vary, 2019).

Recent research in the interaction of light and matter demonstrates significant advances that have profound implications for future technologies. Understanding how light as an agent of energy and information interacts with multiple types of matter at the nanoscale is not only a theoretical achievement but also the foundation for innovation in many fields, including electronics, photovoltaics, sensors, and the medical field. These technological advances were catalyzed by developments in spectroscopy, microscopy, and nanotechnology fabrication methods that enabled the manipulation and measurement of materials with precision that had never been achieved before.

One of the most promising research areas is the development of photonic materials that can manipulate light in highly efficient and selective ways. These newly developed photonic materials can control and direct light with high precision, which is essential for applications such as optical communications and quantum computing. Researchers have successfully created complex nanostructures that can function as waveguides, filters, or highly efficient light sources. This innovation opens the door to smaller, faster, and more efficient devices using less energy.

In the field of renewable energy, a better understanding of how light interacts with semiconductor materials has led to increased efficiency of solar cells. Techniques such as using quantum dots and perovskite solar cells have revolutionized how we capture and convert solar energy into electricity (Cavaliere et al., 2020). Quantum dots, for example, enable the absorption and utilization of a broader spectrum of light than traditional solar cell technology. Further research into the interaction of light with these materials could facilitate the development of even more efficient and sustainable technologies.

In a medical context, technologies such as photonic therapy and diagnostics have experienced major advances thanks to research into the interaction of light and matter. Photonic treatment, which uses light to treat various diseases, including cancer, has shown great potential due to its minimally invasive capabilities and high specificity (Yan et al., 2021). In addition, imaging techniques that combine light with special nanoparticles have enabled the detection of diseases at very early stages with greater accuracy. These two advances promise to increase the effectiveness of treatment and improve patient's quality of life.

Meanwhile, in the manufacturing industry, the ability to use light in processes such as lithography and materials processing has accelerated the production of microelectronics and nanostructures (Xu et al., 2021). These new techniques enable the creation of components with smaller sizes and tighter tolerances, which is critical to meeting the demand for smaller, more powerful devices. This process also offers efficiency and waste reduction advantages, which is consistent with the industry's sustainability goals.

However, despite its great potential, many challenges remain to overcome. Issues such as material stability in long-term applications, cost efficiency in mass production, and integration with existing technologies require serious attention. Continued research and development are needed to overcome these barriers and ensure that innovations in the interaction of light and matter can be translated into practical solutions accessible to the wider public.

CONCLUSIONS

In conclusion, this research not only increases our understanding of the fundamental laws of physics but also pushes the boundaries of technological innovation. By continuing to explore and exploit the interactions between light and matter, we can anticipate significant advances in developing optical devices, data storage technologies, and our approaches to treating disease. In the future, it is critical that researchers continue to collaborate across disciplines, utilize the latest technologies, and encourage applying this knowledge on a broader scale to maximize the benefits of these discoveries for society and industry. As a result, we can expect that the interaction of light and matter will remain a vital and productive area of research, with far-reaching implications for the future of technology.

REFERENCES

Bitzenbauer, P., Veith, J. M., Girnat, B., & Meyn, J.-P. (2022). Assessing Engineering Students' Conceptual Understanding of Introductory Quantum Optics. *Physics*, *4*(4), 1180–1201. https://doi.org/10.3390/physics4040077

Burenkov, I. A., Jabir, M. V., Battou, A., & Polyakov, S. V. (2020). Time-Resolving Quantum Measurement Enables Energy-Efficient, Large-Alphabet Communication. *PRX Quantum*, *1*(1), 010308. https://doi.org/10.1103/PRXQuantum.1.010308

Calderaro, L., Agnesi, C., Dequal, D., Vedovato, F., Schiavon, M., Santamato, A., Luceri, V., Bianco, G., Vallone, G., & Villoresi, P. (2018). Towards quantum communication from global navigation satellite system. *Quantum Science and Technology*, *4*(1), 015012. https://doi.org/10.1088/2058-9565/aaefd4

Casado, A., Guerra, S., & Plácido, J. (2019). From Stochastic Optics to theWigner Formalism: The Role of the Vacuum Field in Optical Quantum Communication Experiments. *Atoms*, *7*(3), 76. https://doi.org/10.3390/atoms7030076

Cavaliere, F., Prati, E., Poti, L., Muhammad, I., & Catuogno, T. (2020). Secure Quantum Communication Technologies and Systems: From Labs to Markets. *Quantum Reports*, *2*(1), 80–106. https://doi.org/10.3390/quantum2010007

Chan, K. S., & Chau, H. F. (2023). Reducing the impact of adaptive optics lag on optical and quantum communications rates from rapidly moving sources. *AIP Advances*, *13*(5), 055201. https://doi.org/10.1063/5.0149695

Di Candia, R., Yiğitler, H., Paraoanu, G. S., & Jäntti, R. (2021). Two-Way Covert Quantum Communication in the Microwave Regime. *PRX Quantum*, *2*(2), 020316. https://doi.org/10.1103/PRXQuantum.2.020316

Galvez, E. J. (2023). A Curriculum of Table-Top Quantum Optics Experiments to Teach Quantum Physics. *Journal of Physics: Conference Series*, *2448*(1), 012006. https://doi.org/10.1088/1742-6596/2448/1/012006

Geraldi, A., Bonavena, L., Liorni, C., Mataloni, P., & Cuevas, Á. (2019). A Novel Bulk-Optics Scheme for Quantum Walk with High Phase Stability. *Condensed Matter*, *4*(1), 14. https://doi.org/10.3390/condmat4010014

Gruneisen, M. T., Eickhoff, M. L., Newey, S. C., Stoltenberg, K. E., Morris, J. F., Bareian, M., Harris, M. A., Oesch, D. W., Oliker, M. D., Flanagan, M. B., Kay, B. T., Schiller, J. D., & Lanning, R. N. (2021). Adaptive-Optics-Enabled Quantum Communication: A Technique for Daytime Space-To-Earth Links. *Physical Review Applied*, *16*(1), 014067. https://doi.org/10.1103/PhysRevApplied.16.014067

Hoskins, J. G., Kaye, J., Rachh, M., & Schotland, J. C. (2023). A fast, high-order numerical method for the simulation of single-excitation states in quantum optics. *Journal of Computational Physics*, *473*, 111723. https://doi.org/10.1016/j.jcp.2022.111723

Hu, C.-Q., Yan, Z.-Q., Gao, J., Jiao, Z.-Q., Li, Z.-M., Shen, W.-G., Chen, Y., Ren, R.-J., Qiao, L.-F., Yang, A.-L., Tang, H., & Jin, X.-M. (2019). Transmission of photonic polarization states through 55-m water: Towards air-to-sea quantum communication. *Photonics Research*, *7*(8), A40. https://doi.org/10.1364/PRJ.7.000A40

Kouadou, T., Diaz, D., & Kwiat, P. (2023). Portable integrated quantum optics for quantum communication. In D. F. Figer & M. Reimer (Eds.), *Photonics for Quantum 2023* (p. 55). SPIE. https://doi.org/10.1117/12.2680341

Li, X., Tong, Z., Lyu, W., Chen, X., Yang, X., Zhang, Y., Liu, S., Dai, Y., Zhang, Z., Guo, C., & Xu, J. (2022). Underwater quasi-omnidirectional wireless optical communication based on perovskite quantum dots. *Optics Express*, *30*(2), 1709. https://doi.org/10.1364/OE.448213

Liu, C., Pang, K., Zhao, Z., Liao, P., Zhang, R., Song, H., Cao, Y., Du, J., Li, L., Song, H., Ren, Y., Xie, G., Zhao, Y., Zhao, J., Rafsanjani, S. M. H., Willner, A. N., Shapiro, J. H., Boyd, R. W., Tur, M., & Willner, A. E. (2019). Single-End Adaptive Optics Compensation for Emulated Turbulence in a Bi-Directional 10-Mbit/s per Channel Free-Space Quantum Communication Link Using Orbital-Angular-Momentum Encoding. *Research*, *2019*, 2019/8326701. https://doi.org/10.34133/2019/8326701

Liu, R., Rozenman, G. G., Kundu, N. K., Chandra, D., & De, D. (2022). Towards the industrialisation of quantum key distribution in communication networks: A short survey. *IET Quantum Communication*, *3*(3), 151–163. https://doi.org/10.1049/qtc2.12044

Manzalini, A. (2020). Quantum Communications in Future Networks and Services. *Quantum Reports*, *2*(1), 221–232. https://doi.org/10.3390/quantum2010014

Martínez Rey, N., Torras, J., Alonso-Sánchez, Á., Magrasó Santa, C., Montilla Garcia, I., & Rodríguez-Ramos, L. F. (2022). Enabling efficient quantum communications with adaptive optics. In H. Hemmati & B. S. Robinson (Eds.), *Free-Space Laser Communications XXXIV* (p. 26). SPIE. https://doi.org/10.1117/12.2608420

Paul, S., & Scheible, P. (2020). Towards Post-Quantum Security for Cyber-Physical Systems: Integrating PQC into Industrial M2M Communication. In L. Chen, N. Li, K. Liang, & S. Schneider (Eds.), *Computer Security – ESORICS 2020* (Vol. 12309, pp. 295–316). Springer International Publishing. https://doi.org/10.1007/978-3-030-59013-0_15

Reiche, S., Knopp, G., Pedrini, B., Prat, E., Aeppli, G., & Gerber, S. (2022). A perfect X-ray beam splitter and its applications to time-domain interferometry and quantum optics exploiting free-electron lasers. *Proceedings of the National Academy of Sciences*, *119*(7), e2117906119. https://doi.org/10.1073/pnas.2117906119

Seguel, A. I., Anguita, J. A., & Pirela, C. S. (2023). Reduction of photon-losses caused by turbulence using spatial diversity in free-space optics quantum communications. In D. T. Wayne, J. A. Anguita, & J. P. Bos (Eds.), *Laser Communication and Propagation through the Atmosphere and Oceans XII* (p. 26). SPIE. https://doi.org/10.1117/12.2677129

Singh, S. K., Azzaoui, A. E., Salim, M. M., & Park, J. H. (2020). Quantum Communication Technology for Future ICT - Review. *Journal of Information Processing Systems*, *16*(6), 1459–1478. https://doi.org/10.3745/JIPS.03.0154

Stejskal, A., Procházka, V., Dudka, M., Vrba, V., Kočiščák, J., Šretrová, P., & Novák, P. (2023). A dual Mössbauer spectrometer for material research, coincidence experiments and nuclear quantum optics. *Measurement*, *215*, 112850. https://doi.org/10.1016/j.measurement.2023.112850

Sun, Y., Yan, L., Chang, Y., Zhang, S., Shao, T., & Zhang, Y. (2019). Two semi-quantum secure direct communication protocols based on Bell states. *Modern Physics Letters A*, *34*(01), 1950004. https://doi.org/10.1142/S0217732319500044

Tao, Z., Chang, Y., Zhang, S., Dai, J., & Li, X. (2019). Two Semi-Quantum Direct Communication Protocols with Mutual Authentication Based on Bell States. *International Journal of Theoretical Physics*, *58*(9), 2986–2993. https://doi.org/10.1007/s10773-019-04178-5

Thomas, O. F., McCutcheon, W., & McCutcheon, D. P. S. (2021). A general framework for multimode Gaussian quantum optics and photo-detection: Application to Hong–Ou–Mandel interference with filtered heralded single photon sources. *APL Photonics*, *6*(4), 040801. https://doi.org/10.1063/5.0044036

Xu, L., Yuan, S., Zeng, H., & Song, J. (2019). A comprehensive review of doping in perovskite nanocrystals/quantum dots: Evolution of structure, electronics, optics, and light-emitting diodes. *Materials Today Nano*, *6*, 100036. https://doi.org/10.1016/j.mtnano.2019.100036

Yamamoto, Y., Leleu, T., Ganguli, S., & Mabuchi, H. (2020). Coherent Ising machines—Quantum optics and neural network Perspectives. *Applied Physics Letters*, *117*(16), 160501. https://doi.org/10.1063/5.0016140

Yanagimoto, R., Ng, E., Wright, L. G., Onodera, T., & Mabuchi, H. (2021). Efficient simulation of ultrafast quantum nonlinear optics with matrix product states. *Optica*, *8*(10), 1306. https://doi.org/10.1364/OPTICA.423044

Yang, Y.-G., Liu, X.-X., Gao, S., Zhou, Y.-H., Shi, W.-M., Li, J., & Li, D. (2021). Towards practical anonymous quantum communication: A measurement-device-independent approach. *Physical Review A*, *104*(5), 052415. https://doi.org/10.1103/PhysRevA.104.052415

Yu, B., Liang, S., Zhang, F., Li, Z., Liu, B., & Ding, X. (2021). Water-stable $CsPbBr_3$ perovskite quantum-dot luminous fibers fabricated by centrifugal spinning for dual white light illumination and communication. *Photonics Research*, *9*(8), 1559. https://doi.org/10.1364/PRJ.427066

Zhao, J., Zhou, Y., Braverman, B., Liu, C., Pang, K., Steinhoff, N., Tyler, G., Willner, A., & Boyd, R. (2020). Investigate the performance of real-time adaptive optics correction in a turbulent high-dimensional quantum communication channel. In H. Hemmati & D. M. Boroson (Eds.), *Free-Space Laser Communications XXXII* (p. 48). SPIE. https://doi.org/10.1117/12.2547186

Zhou, Y., Mirhosseini, M., Oliver, S., Zhao, J., Rafsanjani, S. M. H., Lavery, M. P. J., Willner, A. E., & Boyd, R. W. (2019). Using all transverse degrees of freedom in quantum communications based on a generic mode sorter. *Optics Express*, *27*(7), 10383. https://doi.org/10.1364/OE.27.010383