applied sciences

Editorial

Spectroscopy in Characterization of Materials—Developments

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The intention of the Special Issue "Advances in Spectroscopy for Materials: Bridging Science and Engineering" is to include various enthusiastic works that focus on the use of various analytical spectroscopic techniques while characterizing materials.

Initially, "spectroscopy" was the term coined by Sir Isaac Newton to refer the study of the interaction of light while describing the rainbow of colors [1]. Later, the field of spectroscopy was widely expanded to include different ranges to analyze the interaction of total electromagnetic radiation with all kinds of matter. The conventional spectroscopic techniques from the past century include absorption spectroscopy, fluorescence spectroscopy, nuclear magnetic resonance (NMR) spectroscopy, X-ray fluorescence (XRF) spectroscopy, electron paramagnetic resonance (EPR) spectroscopy, infrared (IR) spectroscopy, Raman spectroscopy, X-ray crystallography, mass spectrometry (MS), and impedance spectroscopy. In addition, many innovative modifications have been made to these traditional spectroscopic techniques in order to evaluate the complex behavior of certain materials.

Historically, spectroscopy has undergone significant development, with each era marked by breakthroughs in instrumentation, methodology, and theoretical understanding. For instance, the advent of quantum mechanics in the early 20th century revolutionized spectroscopic analysis, enabling the interpretation of atomic and molecular spectra with unprecedented precision. Similarly, the development of laser technology in the latter half of the century opened new frontiers in spectroscopy, facilitating ultrafast time-resolved measurements and enabling the study of dynamic processes at the molecular level.

Recent years have witnessed a proliferation of innovative spectroscopic techniques driven by advancements in optics, photonics, and nanotechnology. As spectroscopic techniques continue to evolve and diversify, they offer increasingly sophisticated means of interrogating matter and elucidating fundamental processes across various disciplines. The interdisciplinary nature of spectroscopy ensures its relevance and applicability in fields as diverse as chemistry, biology, physics, and engineering. Here, we elucidate several examples of recent trends in advanced spectroscopic techniques that are changing the perspectives of researchers in terms of innovative materials and solutions.

For instance, terahertz (THz) spectroscopy detects and controls properties of matter with electromagnetic fields that are in the frequency range between a few hundred gigahertz and several terahertz [2]. This technique has garnered significant attention due to its unique capabilities in probing molecular structures and dynamics, which are often inaccessible using other spectroscopic methods. THz spectroscopy systems vary depending on factors such as the type of light source and the intended application. For instance, some systems utilize continuous-wave (CW) sources, while others rely on pulsed sources. Additionally, THz spectroscopy finds applications in diverse fields such as biology to verify information about the composition and structure of biological tissues; in medical inspections to non-invasively detect abnormalities or diseases; in food quality inspection to detect contaminants or adulteration; in security to detect explosives or illicit substances and reveal hidden objects without damage; and in environmental monitoring for the detection of pollutants and the analysis of geological materials.

Another analytical spectroscopic method is single-molecule spectroscopy (SMS). This technique allows the study of individual molecules, providing insights into their behavior

Citation: Krishnapuram, P.; Jakka, S.K. Spectroscopy in Characterization of Materials—Developments. *Appl. Sci.* **2024**, *14*, 4304. https://doi.org/10.3390/app14104304

Received: 12 May 2024
Accepted: 17 May 2024
Published: 19 May 2024

and interactions with unprecedented detail [3]. Advances in fluorescence spectroscopy and super-resolution microscopy have enabled researchers to observe molecular processes in real time at the single-molecule level. In biology, single-molecule spectroscopy has evolved beyond sensitive imaging and analyte detection to include the study of individual molecule dynamics and interactions [4]. By observing single molecules, researchers can capture sequential events, avoiding population averaging issues. Additionally, this approach reveals the conformational states and solvent environments that can affect biological function and optical spectra, particularly at low temperatures. By combining SMS with scanning probe microscopy (SPM), it is possible to measure mechanical and electrical properties, such as binding forces and conductivity [5]. A new possibility of SMS involves enhancing photon analysis capabilities, correlating information like photon arrival time, polarization, wavelength, and excited-state lifetime. Such developments help to interpret biological dynamics at the single-molecule level.

Another budding technique is plasmonic nanospectroscopy, which combines spectroscopy with nanotechnology to achieve high spatial resolution and sensitivity [6]. By coupling light with surface plasmons on metallic nanostructures, the enhancement of spectroscopic signals is achieved to probe nanoscale phenomena with extraordinary precision. Applications span nanophotonics, biosensing, and materials science, allowing the study of individual nanoparticles, molecular vibrations, and surface phenomena. Techniques like surface-enhanced Raman spectroscopy (SERS) and tip-enhanced Raman spectroscopy (TERS) offer label-free, sensitive molecule detection down to the single-molecule level [7]. Plasmonic nanospectroscopy aids in biomedical diagnostics, environmental monitoring, and chemical analysis. Advancements in nanofabrication produce tailored plasmonic nanostructures, enhancing optical properties for specific applications. Integration with fluorescence and electron microscopy offers comprehensive insights into nanoscale phenomena. In summary, plasmonic nanospectroscopy is a powerful tool driving understanding and innovation across disciplines, promising new capabilities in fundamental research and applied sciences.

Known for half a century, the evolution of ultrafast spectroscopy towards quantum spectroscopy hinges on the ability to manipulate quantum correlations of light, including entanglement, in light pulses of varying waveforms and intensities [8]. This crucial advancement opens avenues for exploring the direct detection and manipulation of many-body states, thus serving as a precise resource for quantum information science. Both theoretical frameworks and experimental methodologies are being developed to enable the realization of all-experimental quantum spectroscopy, particularly in semiconductor systems. This innovative technique meets the rigorous criteria for achieving direct, user-defined quantum-optical excitations of many-body states, marking a significant advancement towards harnessing the full potential of quantum spectroscopy in materials science and beyond.

The evolution and expansion of spectroscopic techniques over time portray the dynamic nature of scientific inquiry and technological innovation. As research requirements evolve and new challenges emerge, spectroscopy continually adapts and advances to meet the demands of diverse fields ranging from fundamental physics to applied materials science and biomedical research.

Acknowledgments: The authors acknowledge the funding from national funds (OE), through FCT—Fundação para a Ciência e a Tecnologia, Portugal, I.P., in the scope of the framework contract foreseen in the numbers 4, 5, and 6 of Article 23 of the Decree-Law 57/2016, of August 29, changed by Law 57/2017, of July 19. This work was developed within the scope of the project i3N, UIDB/50025/2020 and UIDP/50025/2020, financed by national funds through the FCT/MEC.

Conflicts of Interest: The authors declare no conflicts of interest.

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