15.7: Modern Applications of Laser Spectroscopy

A Quick Overview

Laser light offers valuable tools to researchers who wish to use the interaction of light with matter to interrogate atomic and molecular systems. Most laser light is characterized by its near monochromaticity (relative to light from other sources), directionality, and coherence [1]. Those characteristics are used in modern laser spectroscopy. The monochromaticity of laser light allows it to be used to probe specific energy changes in atoms and molecules. This ability to select specific wavelengths allows scientists to focus on chosen components in mixtures, including complex reaction mixtures. For example, Park et. al. tracked the dynamics of the reaction of ground state oxygen with ethyl radical by using a 355 nm laser beam to track one of the products of this reaction [2]. Parsons et. al. used near monochromatic laser light sources to achieve state-selective ionization for the study of the products of a photodissociation reaction of atmospheric relevance [3]. Laser monochromaticity can be used to quantify the amount of greenhouse gases in the atmosphere [4]. Even when the samples are not mixtures, monochromaticity allows researchers to gather detailed information about atomic and/or molecular structure. Applications of this type are extremely numerous, including detailed studies of atomic systems [5], semiconductor materials [6], single molecules [7], and biological molecules [8]. Lasers find research applications in art and archeology, where the property of monochromaticity allows specific energies to be probed and laser beam directionality and small spot size curtail destruction of samples [9,10].

Other laser applications focus on the ability of pulsed lasers to provide short pulses. Short-pulsed lasers offer myriad tools for exploring chemical kinetics at a range of timescales, including very short ones. Short-pulse lasers open the opportunity for time-resolved studies of molecular processes such as reaction processes [2,11] and biological processes [12 - 15], and the properties of excited states [16]. Some research applications take advantage of the ability of certain lasers to produce high intensity light. One such application is laser-induced break down spectroscopy (LIBS), in which the high intensity of the laser creates a plasma from solid or liquid samples; that plasma can subsequently be probed [17]. Other techniques that exploit high laser intensities are the nonlinear spectroscopies, where the high intensities of some lasers can produce behaviors in samples that lower-power sources cannot sufficiently stimulate [18,19]. Although most lasers are monochromatic and coherent, some researchers have modified laser light to obtain information from broadband, incoherent laser light [20 – 22], which allows them to probe the response of samples to light that more resembles sunlight (incoherent) than do traditional laser sources [22, 23]. Another possibility is to probe multiple wavelengths with broadband laser sources that are coherent [24].

Conclusion

This brief overview has only skimmed the surface of the vast field of laser spectroscopy. The examples given here are a very small, somewhat arbitrary, and significantly biased subset of the enormous library of published laser-based experiments. References have been chosen to give examples of the topics covered here and have not been extensively reviewed by the author.

Overall, lasers are especially useful as light sources when one or more of the following properties are desired for light in an experiment:

1. A high degree of monochromaticity
2. A well-known central wavelength for a light source
3. A tunable light source
4. Spatial coherence
5. Phase coherence
6. Directionality
7. High intensity
8. Tight focus
9. Short pulses

A particular laser type will not necessarily have all the properties in the list above; however, the menu of available laser types allows a researcher to choose a laser system or systems with the characteristics needed for a particular experiment. New applications of laser spectroscopy and new spectroscopic techniques employing laser light continue to be invented.

References

[1] https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Analytical_Sciences_Digital_Library/JASDL/Courseware/Introduction_to_Lasers/03_Basic_Principles/01_Laser_Radiation_Properties

[2] *J. Phys. Chem. A* 2010, 114, 14, 4891–4895; Publication Date: February 19, 2010; https://doi.org/10.1021/jp910615y

[3] *J. Phys. Chem. A* 2022, 126, 34, 5729–5737; Publication Date: August 22, 2022; https://doi.org/10.1021/acs.jpca.2c04265

[4] https://www.nist.gov/news-events/news/2021/06/nist-laser-comb-systems-now-measure-all-primary-greenhouse-gases-air

[5] R. C. Thompson, 1985 *Rep. Prog. Phys.* **48** 531; https://iopscience.iop.org/article/10.1088/0034-4885/48/4/003

[6] *J. Phys. Chem. A* 2020, 124, 15, 2972–2981; Publication Date: March 23, 2020; https://doi.org/10.1021/acs.jpca.0c00370

[7] *J. Phys. Chem. A* 1997, 101, 45, 8435–8440; Publication Date: November 6, 1997; https://doi.org/10.1021/jp9719063

[8] Jörg Standfuss, Membrane protein dynamics studied by X-ray lasers – or why only time will tell, *Current Opinion in Structural Biology*, Volume 57, 2019, Pages 63-71, ISSN 0959-440X, https://doi.org/10.1016/j.sbi.2019.02.001

[9] https://www.getty.edu/conservation/about/science/laser_mass.html

[10] https://www.laserfocusworld.com/test-measurement/spectroscopy/article/14183101/spectroscopy-uncovers-the-hidden-in-art-and-archaeology

[11] *J. Phys. Chem.* 1996, 100, 31, 12701–12724; Publication Date: August 1, 1996; https://doi.org/10.1021/jp960658s

[12] Hideki Hashimoto, Mitsuru Sugisaki, Masayuki Yoshizawa,

Ultrafast time-resolved vibrational spectroscopies of carotenoids in photosynthesis, *Biochimica et Biophysica Acta - Bioenergetics*, Volume 1847, Issue 1, 2015, Pages 69-78,

ISSN 0005-2728, https://doi.org/10.1016/j.bbabio.2014.09.001.

[13] *J Phys Chem A*. 2003 Oct 9; 107(40): 8208–8214.; Publication Date: June 12, 2003 ; https://doi.org/10.1021/jp030147n

[14] *Biochemistry* 2003, 42, 34, 10054-10059; Publication Date: August 5, 2003; https://doi.org/10.1021/bi034878p

[15] Holzwarth, A. (1989). Applications of ultrafast laser spectroscopy for the study of biological systems. *Quarterly Reviews of Biophysics, 22*(3), 239-326.

https://doi.org/10.1017/S0033583500002985

[16] *J. Phys. Chem. B* 2015, 119, 29, 9335–9344; Publication Date:November 4, 2014; https://doi.org/10.1021/jp509959n

[17] *Anal. Chem.* 2013, 85, 2, 640–669; Publication Date:November 8, 2012; https://doi.org/10.1021/ac303220r

[18]https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Book%3A_Nonlinear_and_Two-Dimensional_Spectroscopy_(Tokmakoff)/00%3A_Front_Matter/05%3A_What_is_Nonlinear_Spectroscopy

[19] Marc Levenson and Satoru Kano, *Introduction to Nonlinear Laser Spectroscopy*, revised edition, 2012, Academic Press, ISBN-13: 978-0124447226, ISBN-10: 0124447228

[20] *J. Phys. Chem. A* 2013, 117, 29, 5926–5954; Publication Date: November 26, 2012; https://doi.org/10.1021/jp310477y

[21] Turner, D., Arpin, P., McClure, S. *et al.* Coherent multidimensional optical spectra measured using incoherent light. *Nat Commun* **4**, 2298 (2013). https://doi.org/10.1038/ncomms3298

[22] *J. Phys. Chem. Lett.* 2012, 3, 21, 3136–3142; Publication Date: October 9, 2012; https://doi.org/10.1021/jz3010317

[23] *J. Phys. Chem. Lett.* 2018, 9, 11, 2946–2955; Publication Date: May 15, 2018; https://doi.org/10.1021/acs.jpclett.8b00874

[24] Muraviev, A.V., Konnov, D. & Vodopyanov, K.L. Broadband high-resolution molecular spectroscopy with interleaved mid-infrared frequency combs. *Sci Rep* **10**, 18700 (2020). https://doi.org/10.1038/s41598-020-75704-3

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