Journal link: http://kmf-publishers.com/tatscr/

Theoretical and Applied Technological Science Review

Volume: 2 Issue: 1 Year: 2024
ISSN-2958-7824

KMF PUBLISHERS www.kmf-publishers.com/tatscr/

Received: 10 January 2024 | Revised: 22 February 2024 | Accepted: 24 March 2024

DOI: https://doi.org/10.5281/zenodo.11060176

Article

To Develop Nobel Prize "ATTOSECOND" Theory By Verilog Programming & Verify by Test Programming

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ABSTRACT

Attosecond generation is a technique to generate an attosecond pulse of different time intervals by changing the wave length of different types of radiation waves. To develop Attosecond generation equation by Verilog programming. In order to develop the equation in to programming language by define the all the parameter in Verilog system. All the bits of the input and output are fix bits. All the interfacing parameters between equations into the Verilog syntex is fixing. Interfacing between Verilog programming and Test bench programming is verifying the Verilog programming of the equation by the test bench programming. Electronic Design Automation software is used to get the output of Verilog programming. Electronic Design Automation software is used to get the output of Test bench programming. Output of Verilog programming and output of the test bench programming is verifying the programming of equation of Attosecond generation pulse. Both output of Verilog and test bench programming shown in wave form on the software.

Keywords: Attosecond, Verilog Programming, Test Bench Programming, Software, Verification, Epwave form

INTRODUCTION

The attosecond pulse generation is generating a traveling pulse with ultra-short time duration, two key elements are needed: bandwidth and central wavelength of the electromagnetic wave. Attosecond physics, also known as attophysics, or more generally attosecond science, is a branch of physics that deals with light-matter interaction phenomena wherein attosecond (10-18 s) photon Pulses are used to unravel dynamical processes in matter with unprecedented time resolution. Attosecond science mainly employs pump–probe spectroscopic methods to investigate the physical process of interest. Due to the complexity of this field of study, it generally requires a synergistic interplay between state-of-the-art experimental setup and advanced theoretical tools to interpret the data collected from attosecond experiments. The main interests of attosecond physics are: Atomic physics: investigation of electron correlation effects, photo-emission delay and tunneling. Molecular and molecular chemistry: role of electronic motion in molecular excited states (e.g. charge-transfer processes), light-induced photo-fragmentation, and light-induced electron transfer processes. Solid: investigation of exaction dynamics in advanced 2D materials, petahertz charge carrier motion in solid,spin dynamics in ferromagnetic materials. One of the primary goals of attosecond science is to provide advanced insights into the quantum dynamics of electrons in atoms, molecules and solids with the long-term challenge of achieving real-time control of the electron motion in matter. Interfacing between equation of attosecond generation and Verilog programming. It is never developed any type of programming language of this equation and never verified by test bench programming. My object to develop the Verilog programming of this equation and verify by test bench programming. The scope of this research is interfacing of multiple programming language and conversion from one domain to another domain.

LITERATURE REVIEW

Ti: sapphire lasers (also known as Ti:Al2O3 lasers, titanium titanium-sapphire lasers, or Ti: sapphs) are tunable lasers which emit red and near-infrared light in the range from 650 to 1100 nanometers. These lasers are mainly used in scientific research because of their tenability and their ability to generate ultra-short pulses. Lasers based on Ti: sapphire were first constructed and invented in June 1982 by Peter Moulton at the MIT Lincoln Laboratory .Titanium-sapphire refers to the lasing medium, a crystal of sapphire (Al2O3) that is doped with Ti3+ ions. A Ti: sapphire laser is usually pumped with another laser with a wavelength of 514 to 532 nm, for which argon ion lasser(514.5 nm)and frequency doubled Nd:YAG, Nd:YL, and Nd:YVO lasers (527-532 nm) are used. They are capable of laser operation from 670 nm to 1,100 nm wavelength. Ti:sapphire lasers operate most efficiently at wavelengths near 800 nm. Chirped pulse amplification (CPA) is a technique for amplifying an ultra-ultra short laser pulse up to the Petawatt level, with the laser pulse being stretched out temporally and spectrally, then amplified, and then compressed again. The stretching and compression uses devices that ensure that the different color components of the pulse travel different distances. PA for lasers was introduced by Donna Strickland and Gérard Mourou at the University of Rochester in the mid-1980s,work for which they received the Nobel Prize in Physics in 2018.Self-phase modulation (SPM) is a nonlinear optical effect of light–matter interaction. An ultrashort pulse of light, when travelling in a medium, will induce a varying refractive index of the medium due to the optical Kerr effect. This variation in refractive index will produce a phase shift in the pulse, leading to a change of the pulse's frequency spectrum. Self-phase modulation is an important effect in optical systems that use short, intense pulses of light, such as lasers and optical fiber communications systems. Self-phase modulation has also been reported for nonlinear sound waves propagating in biological thin films, where the phase modulation results from varying elastic properties of the lipid films. A chirped mirror is a dielectric mirror with chirped Spaces-spaces of varying depth designed to reflect varying wavelengths of lights—between the dielectric layers (stack). Chirped mirrors are used in applications like lasers to reflect a wider range of light wave Lengths than ordinary dielectric mirrors, or to compensate for the dispersion of wavelengths that can be created by some optical elements.Chirped mirrors are also found in structurally colored biological systems,including the shiny golden and silver color of certain beetles' elytra, e.g. those of the Ruteline genus Chrysina. In these cases, the chirped mirror generates complex color (such as gold or silver) when illuminated by white light by simultaneously reflecting a broad range of monochromatic colors. In optics, a frequency comb is a laser source whose spectrum consists of a series of discrete, equally spaced frequency lines. Frequency combs can be generated by a number of mechanisms, including periodic modulation (in amplitude and/or phase) of a continuous-wave laser, four-wave mixing in nonlinear media, or stabilization of the pulse train generated by a mode-locked laser. Much work has been devoted to this last mechanism, which was developed around the turn of the 21st century and ultimately led to one half of the Nobel Prize in Physics being shared by John L. Hall and Theodor W. Hänsch in 2005.The frequency domain representation of a perfect frequency comb is a series of delta functions spaced according to fn=f0+nfr, where n is an integer, fr is the comb tooth spacing (equal to the mode-locked laser's repetition rate or the modulation frequency), and f0 is the carrier offset frequency, which is less than fr.Combs spanning an octave in frequency (i.e., a factor of two) can be used to directly measure (and correct for drifts in) f0. Thus, octave-spanning combs can be used to steer a piezoelectric mirror within a carrier–envelope phase-correcting feedback loop. Any mechanism by which the combs' two degrees of freedom (fr and f0) are stabilized generates a comb that is useful for mapping optical frequencies into the radio frequency for the direct measurement of optical frequency. High-harmonic generation (HHG) is a non-linear process during which a target (gas, plasma, solid or liquid sample) is illuminated by an intense laser pulse. Under such conditions, the sample will emit the high harmonics of the generation beam (above the fifth harmonic). Due to the coherent nature of the process, high-harmonics generation is a prerequisite of attosecond physics. Anne Geneviève L'Huillier ([an lɥi.je]; born 16 August 1958) is a French-Swedish physicist, and professor of atomic physics at Lund University in Sweden. She leads an attosecond physics group which studies the movements of electrons in real time, which is used to understand the chemical reactions on the atomic level. Her experimental and theoretical research are credited with laying the foundation for the field of astrochemistry.In 2003 she and her group beat the world record for the shortest laser pulse, of 170 attoseconds. L'Huillier became a member of the Royal Swedish Academy of Sciences in 2004.She has received various physics awards including the Wolf Prize in Physics in 2022and the Nobel Prize in Physics in 2023.The Nobel Prize in Physics (Swedish: Nobelpriset i fysik) is a yearly award given by the Royal Swedish Academy of Sciences for those who have made the most outstanding contributions for humankind in the field of physics. It is one of the five Nobel Prizes established by the will of Alfred Nobel in 1895 and awarded since 1901, the others being the Nobel Prize in Chemistry, Nobel Prize in Literature, Nobel Peace Prize, and Nobel Prize in Physiology or Medicine. Physics is traditionally the first award presented in the Nobel Prize ceremony. The prize consists of a medal along with a diploma and a certificate for the monetary award. The front side of the medal displays the same profile of Alfred Nobel depicted on the medals for Physics, Chemistry, and

Literature. The first Nobel Prize in Physics was awarded to German physicist Wilhelm Röntgen in recognition of the extraordinary services he rendered by the discovery of X- rays. This award is administered by the Nobel Foundation and is widely regarded as the most prestigious award that a scientist can receive in physics. It is presented in Stockholm at an annual ceremony on 10 December, the anniversary of Nobel's death. As of 2023, a total of 224 individuals have been awarded the prize.

METHODOLOGY

Attosecond pulse generation equation is interfacing with Verilog programming. All the parameter of the equation Is mapping by Verilog parameter. Data bits of parameter are fixing accordance with Verilog parameter bit. Interconnection between Verilog programming and test bench programming. All these parameter is fixing by both domain bits in distinguish ways. Parameter of attosecond generation equation and test bench programming language is determined by its own domain. The output of the Verilog programming is display on the Electronic design automation software in the Epwave form .Similarly the output of the test bench is shows on Electronic design automation software in the Epware form. Verification of the equation programming in Verilog and test bench programming is match with each other after that display the output.

FINDING

Output of the verification of Verilog programming and test bench programming in binary digit and hexa digit is given below:

Fig1: Hexa Bit output

Fig.2 Binary-bit output

DISCUSSION

Epwave form generated the output of Verilog programming of the equation in the proper bit format in the form of the binary digit and hexa decimal digit. Verification of both programming of the equation is display in definite time interval .Output of the bit in shows in various time duration.

CONCLUSION

The study undertaken contributes the positive outcome of the Epwave form of the Verilog programming and test bench programming and development of the equation of the Attosecond pulse generation verified by the output of the software of the electronic design automation.

ACKNOWLEDGMENT

I would like to express my sincere thanks to my entire supporter to help in this work.

REFERENCES

1. ^Jump up to:a b Krausz F, Ivanov M (February 2009). "Attosecond physics". Reviews of Modern Physics. 81 (1): 163– 234. Bibcode:2009RvMP...81..163K. doi:10.1103/RevModPhys.81.163.
2. ^ Jump up to:a b Schultze M, Fiess M, Karpowicz N, Gagnon J, Korbman M, Hofstetter M, et al. (June 2010). "Delay in photoemission" (PDF). Science. 328 (5986): 1658–62. Bibcode:2010Sci...328.1658S. doi:10.1126/science.1189401. PMID 20576884. S2CID 9984886.
3. ^ Nisoli M, Decleva P, Calegari F, Palacios A, Martín F (August 2017). "Attosecond Electron Dynamics in Molecules" (PDF). Chemical Reviews. 117 (16): 10760– 10825. doi:10.1021/acs.chemrev.6b00453. hdl:11311/1035707. PMID 28488433.
4. ^ Ghimire S, Ndabashimiye G, DiChiara AD, Sistrunk E, Stockman MI, Agostini P, et al. (2014-10-08). "Strong-field and attosecond physics in solids". Journal of Physics B: Atomic,

Molecular and Optical Physics. 47 (20):204030. Bibcode:2014JPhB...47t4030G. doi:10.1088/0953-4075/47/20/204030. ISSN 0953-4075.

5. ^ Jump up to:a b Agostini P, DiMauro LF (2004). "The physics of attosecond light pulses". Reports on Progress in Physics. 67 (6): 813–855. Bibcode:2004RPPh...67..813A. doi:10.1088/0034-4885/67/6/R01. S2CID 53399642.
6. ^ Moulton PF (January 1986). "Spectroscopic and laser characteristics of Ti:Al_2O_3". Journal of the Optical Society of America B. 3 (1): 125. Bibcode:1986JOSAB...3..125M. doi:10.1364/josab.3.000125. ISSN 0740-3224.
7. ^ Maine P, Strickland D, Pessot M, Squier J, Bado P, Mourou G, Harter D (1988). "Chirped Pulse Amplification: Present and Future". Ultrafast Phenomena VI. Berlin, Heidelberg: Springer Berlin Heidelberg. pp. 2–7. ISBN 978-3-642-83646-6. broadband dispersion control in femtosecondlasers". Optics Letters. 19 (3):201. Bibcode:1994OptL...19..201S. doi:10.1364/ol.19.000201. PMID 19829591.
8. ^Nisoli M, De Silvestri S, Svelto O (1996-05-13). "Generation of high energy 10 fs pulses by a new pulse compression technique". Applied Physics Letters. 68 (20): 2793–2795. Bibcode:1996ApPhL..68.2793N. doi:10.1063/1.116609. ISSN 0003-6951. S2CID 118273858.
9. ^ Szipocs R, Ferencz K, Spielmann C, Krausz F (February 1994). "Chirped multilayer coatings for
10. ^ Baltuska A, Udem T, Uiberacker M, Hentschel M, Goulielmakis E, Gohle C, et al. (February 2003). "Attosecond control of electronic processes by intense light fields". Nature. 421 (6923): 611–5. Bibcode:2003Natur.421..611B. doi:10.1038/natu re01414. PMID 12571590. S2CID 4404842.
11. ^ Kienberger R, Goulielmakis E, Uiberacker M, Baltuska A, Yakovlev V, Bammer F, et al. (February 2004). "Atomic transient recorder". Nature. 427 (6977): 817–21. Bibcode:2004Natur.427..817K. doi:10.1038/nat ure02277. PMID 14985755. S2CID 4339323.
12. ^ Sansone G, Benedetti E, Calegari F, Vozzi C, Avaldi L, Flammini R, et al. (October 2006). "Isolated single-cycle attosecond pulses". Science. 314 (5798): 443– 6. Bibcode:2006Sci...314..443S. doi:10.1126/science.1132838. hdl:11577/1565991. PMID 17053142. S2CID 2351301.
13. ^ Krausz F (2016-05-25). "The birth of attosecond physics and its coming of age". Physica Scripta. 91 (6): 063011. Bibcode:2016PhyS...91f3011K. doi:10.1088/0031-8949/91/6/063011. ISSN 0031-8949. S2CID 124590030.
14. ^ Gaumnitz T, Jain A, Pertot Y, Huppert M, Jordan I, Ardana-Lamas F, Wörner HJ (October 2017). "Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver". Optics Express. 25 (22): 27506–27518. Bibcode:2017OExpr..2527506G. doi:10.1364/OE.25.027506. hdl:20.500.11850/211882. PMID29092222.
15. ^ Johnson AS, Avni T, Larsen EW, Austin DR, Marangos JP (May 2019). "Attosecond soft X-ray high harmonic generation". Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences. 377 (2145): 20170468. Bibcode:2019RSPTA.37770468J. doi:10.1098/rsta.2017.0468. PMC 6452054. PMID 30929634.
16. ^ Jump up to:a b Sansone G, Kelkensberg F, Pérez-Torres JF, Morales F, Kling MF, Siu W, et al. (June 2010). "Electron localization following attosecond molecular photoionization" (PDF). Nature. 465 (7299): 763–6. Bibcode:2010Natur.465..763S. doi:10.1038/nature09084. PMID 20535207. S2CID 205220785.
17. ^ Jump up to:a b Calegari F, Ayuso D, Trabattoni A, Belshaw L, De Camillis S, Anumula S, et al.

(October 2014). "Ultrafast electron dynamics in phenylalanine initiated by attosecond pulses". Science. 346 (6207): 336–9. Bibcode:2014Sci...346..336C. doi:10.1126/science.1254061. hdl:10486/679967. PMID 25324385. S2CID 5371103.

18. ^ Kobayashi Y, Chang KF, Zeng T, Neumark DM, Leone SR (July 2019). "Direct mapping of curve-crossing dynamics in IBr by attosecond transient absorption spectroscopy". Science. 365 (6448): 79–83. Bibcode:2019Sci...365...79K. doi:10.1126/scie nce.aax0076. PMID 31273121. S2CID 195804243.
19. ^ Jump up to:a b Lucchini M, Sato SA, Lucarelli GD,Moio B, Inzani G, Borrego-Varillas R, et al. (February 2021). "Unravelling the intertwined atomic and bulk nature of localised excitons by attosecond spectroscopy". Nature Communications. 12 (1): 1021. arXiv:2006.16008. Bibcode:2021NatCo..12.1021L. doi:10.1038/s41467-021-21345-7. hdl:10810/50745. PMC 7884782. PMID 33589638.
20. ^ Lucarelli GD, Moio B, Inzani G, Fabris N, Moscardi L, Frassetto F, et al. (May 2020). "Novel beamline for attosecond transient reflection spectroscopy in a sequential two-foci geometry". The Review of Scientific Instruments. 91 (5): 053002. arXiv:2002.10869. Bibcode:2020RScI...91e3002L. doi:10.1063/5.0005932. PMID 32486725. S2CID 211296620.
21.): e1430. doi:10.1002/wcms.1430. ISSN 1759-0884. S2CID 199653256.
22. ^ Sato SA (2021). "First-principles calculations for attosecond electron dynamics in solids". Computational Materials Science. 194: 110274. arXiv:2011.01677. doi:10.1016/j.commatsci.2020.110274. ISSN 09270256. S2CID 226237040.
23. ^ Mourou G. "ICAN: The Next Laser Powerhouse". Archived from the original on 2021-06-24.
24. ^ Reiss HR (2008). "Foundations of the Strong-Field Approximation". In Yamanouchi K, Chin SL, Agostini P, Ferrante G (eds.). Progress in Ultrafast Intense Laser Science III. Springer Series in Chemical Physics. Vol. 89. Berlin, Heidelberg: Springer. pp. 1–31. doi:10.1007/978-3-540- 73794-0_1. ISBN 978-3-540-73794-0.
25. ^ Maurer J, Keller U (2021-05-05). "Ionization in intense laser fields beyond the electric dipole approximation: concepts, methods, achievements and future directions". Journal of Physics B: Atomic, Molecular and Optical Physics. 54 (9): 094001. doi:10.1088/1361-6455/abf731. hdl:20.500.11850/489253. ISSN 0953-4075. S2CID 235281853.
26. ^ Jump up to:a b Ivanov MY, Spanner M, Smirnova O (2005-01-20). "Anatomy of strong field ionization". Journal of Modern Optics. 52 (2–3):165–184. Bibcode:2005JMOp...52..165I. doi:10.1080/0950034042000275360. ISSN 0950-0340. S2CID 121919221.
27. ^ Jump up to:a b c d e f Mulser P, Bauer D (2010). High Power Laser-Matter Interaction. Springer Tracts in Modern Physics. Vol. 238. Berlin Heidelberg: Springer-Verlag. Bibcode:2010hpli.book.....M. doi:10.1007/978-3-540-46065-7. ISBN 978-3-540-50669-0.
28. ^ Faisal FH (2007-03-15). "Gauge-invariant intense-field approximations to all orders". Journal of Physics B: Atomic, Molecular and Optical Physics. 40 (7): F145–F155. doi:10.1088/0953-4075/40/7/f02. ISSN 0953-4075. S2CID 117984887.
29. ^ V Popruzhenko, S (2014-10-08). "Keldysh theory of strong field ionization: history, applications, difficulties and perspectives". Journal of Physics B: Atomic, Molecular and Optical Physics. 47 (20):204001. Bibcode:2014JPhB...47t4001P. doi:10.1088/0953-

4075/47/20/204001. ISSN 0953-4075. S2CID 250736364.
30. ^ V Popruzhenko, S (2014-10-08). "Keldysh theory of strong field ionization: history, applications, difficulties and perspectives". Journal of Physics B: Atomic, Molecular and Optical Physics. 47 (20):204001. Bibcode:2014JPhB...47t4001P. doi:10.1088/0953-4075/47/20/204001. ISSN 0953-4075. S2CID 250736364.
31. ^ Amini K, Biegert J, Calegari F, Chacón A, Ciappina MF, Dauphin A, et al. (November 2019). "Symphony on strong field approximation". Reports on Progress in Physics. 82 (11):116001. arXiv:1812.11447. Bibcode:2019RPPh...82 k6001A. doi:10.1088/1361-6633/ab2bb1. PMID 31226696. S2CID 118953514.
32. ^ University of Kassel. "Physical phenomena in laser-matterinteraction" (PDF). Archived (PDF) from the original on 2011-01-01.
33. ^ Jackson JD (1999). Classical electrodynamics (3 ed.). New York: Wiley. ISBN 0-471-30932-X. OCLC 38073290.
34. ^ Milošević DB, Becker W (2019-04-10). "Atom-Volkov strong-field approximation for above-threshold ionization". Physical Review A. 99 (4):043411. Bibcode:2019PhRvA..99d3411M. doi:10.1103/physreva.99.043411. ISSN 2469-9926. S2CID 146011403.35. ^ Bechler A, Ślęczka M (2009-12-25). "Gauge invariance of the strong field approximation". arXiv:0912.4966 [physics.atom- ph].
36. ^ Brabec T, Krausz F (2000-04-01). "Intense few-cycle laser fields: Frontiers of nonlinear optics". Reviews of Modern Physics. 72 (2): 545–591. Bibcode:2000RvMP...72..545B. doi:10.1103/RevModPhys.72.545. ISSN 0034-6861.
37. ^ Jump up to:a b c Yakovlev VS, Gagnon J, Karpowicz N, Krausz F (August 2010). "Attosecond streaking enables the measurement of quantum phase". Physical Review Letters. 105 (7):073001. arXiv:1006.1827. Bibcode:2010PhRvL.105 g3001Y. doi:10.1103/PhysRevLett.105.073001. PM ID 20868037. S2CID 12746350.
38. ^ Keller U (2015-05-10). "Attosecond Ionization Dynamics and Time Delays". CLEO: 2015 (2015), Paper FTh3C.1. Optical Society of America: FTh3C.1. doi:10.1364/CLEO_QELS.2015.FTh3C.1. IS BN 978-1-55752-968-8. S2CID 39531431.
39. ^ Kheifets AS (2020-03-06). "The attoclock and the tunneling time debate". Journal of Physics B: Atomic, Molecular and Optical Physics. 53 (7):072001. arXiv:1910.08891. Bibcode:2020JPhB...53 g2001K. doi:10.1088/1361-6455/ab6b3b. ISSN 0953-4075. S2CID 204800609.
40. ^ Jump up to:a b Mairesse Y, Quéré F (2005-01-27). "Frequency-resolved optical gating for complete reconstruction of attosecond bursts". Physical Review A. 71 (1): 011401. Bibcode:2005PhRvA..71a1401M. doi:10.1103/PhysRevA.71.011401.
41. ^ Jump up to:a b Itatani J, Quéré F, Yudin GL, Ivanov MY, Krausz F, Corkum PB (April2002). "Attosecond streak camera". Physical Review Letters. 88 (17):173903. Bibcode:2002PhRvL..88q3903I. doi:10.1103/PhysRevLett.88.173903. PMID 12005756. S2CID40245650. 42. ^ Vismarra, F.; Borrego-Varillas, R.; Wu, Y.; Mocci, D.; Nisoli, M.; Lucchini, M. (2022). "Ensemble effects on the reconstruction of attosecond pulses and photoemission time delays". Journal of Physics: Photonics. 4 (3):034006. Bibcode:2022JPhP....4c4006V. doi:10.1088/2515-7647/ac7991. hdl:11311/1219391. S2CID 249803416.
43. ^ Trebino R (2003). "FROG". Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses. Boston, MA: Springer US. pp. 101–115. doi:10.1007/978-1-4615-1181-6_5. ISBN 978-1-4613-5432-1.

44. ^ Zhao X, Wei H, Wei C, Lin CD (2017-10-23). "A new method for accurate retrieval of atomic dipole phase or photoionization group delay in attosecond photoelectron streaking experiments". Journal of Optics. 19 (11):114009. Bibcode:2017JOpt...19k4009Z. doi:10.1088/2040-8986/aa8fb6. ISSN 2040-8978. S2CID 125209544.
45. ^ Kane DJ (2008-06-01). "Principal components generalized projections: a review [Invited]". JOSA B. 25 (6): A120–A132. Bibcode:2008JOSAB..25A.120K. doi:10.1364/JOSAB.25.00A120. ISSN 1520-8540.
46. ^ Keathley PD, Bhardwaj S, Moses J, Laurent G, Kaertner FX (2016-07-06). "Volkov transform generalized projection algorithm for attosecond pulse characterization". New Journal of Physics. 18 (7):073009. Bibcode:2016NJPh...18g3009K. doi:10.1088/1367-2630/18/7/073009. hdl:1721.1/105139. ISSN 1367-2630. S2CID 53077495.
47. ^ Lucchini M, Brügmann MH, Ludwig A, Gallmann L, Keller U, Feurer T (November 2015). "Ptychographic reconstruction of attosecond pulses". Optics Express. 23 (23): 29502–13. arXiv:1508.07714. Bibcode:2015OExpr..2329502L. doi:10.1364/OE.23.029502. PMID 26698434. S2CID 33845261.
48. "Attosecond spectroscopy wins 2023's Nobel Prize in Physics". Big Think. 3 October 2023. Retrieved 3 October 2023
49. https://www.mpg.de/20915252/nobel-prize-physics-2023-ferenc-krausz