Nonlinear photonics in undergraduate curriculum: hands-on training to meet the demands of a qualified workforce

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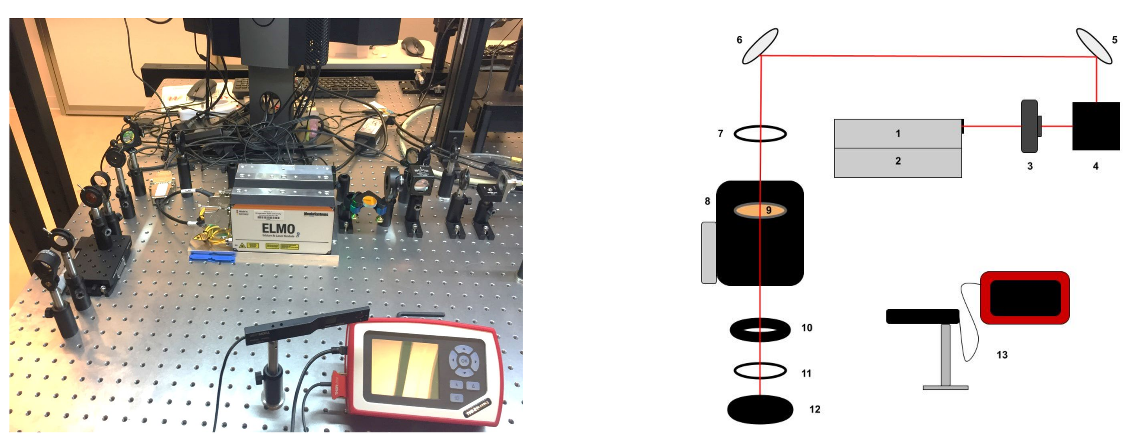
Introduction

In recent years, integrated photonics through the study of nonlinear optics has proven itself as a promising platform for development of complex engineering tasks demanded by the high growth of industry interest on revolutionary technologies (e.g., quantum communications, neurophotonics, ultra-fast devices). Nonlinear optics is commonly approached at postgraduate level, and not at the undergraduate level. The importance of undergraduate research provides the opportunity for students to understand the research process at an early stage of their career, how scientist work on problems, develop skills as laboratory techniques and results interpretation, among other important skills required in both academia and industry. With the aim of contributing to the construction of a responsive curriculum for a qualified workforce, we propose a laboratory practice based on the implementation of the Z-Scan technique, which may be used as reference for the development of updated hands-on courses on advanced photonics.

(a) (b) (c)

Figure 1: Photonic Integrated Circuit from AIM Photonics (a), undergraduate student conducting nonlinear optical experiment (b) and Quantum Entanglement alignment with qutools educational experiment in undergraduate course (c).

Experimental Setup



(a) (b)

Figure 2: Z-Scan Experimental Setup (a) and Z-Scan Experimental Setup Diagram (b).

Table 1. Experimental Setup Diagram Legend.

1 Menlo Systems Amplifier ELMA	**2** Menlo Systems FS Laser ELMO	**3** Rotating Half-Wave Plate	**4** Polarizing Beam Splitter
5,6 Post-Mounted Optical Mirror	**7** Post-Mounted Optical Lens	**8** Thorlabs 1D Translation Stage	**9** Post-Mounted Sample
10 Post-Mounted Adjustable Iris	**11** Post-Mounted Optical Lens	**12** Post-Mounted Beam Blockers	**13** Thorlabs Power Meter

The Z-scan experimental contains two processes. With an open aperture, the sample is moved along the propagation axis, passing through the focal plane. The scan is performed under the same conditions, but keeping the aperture closed.

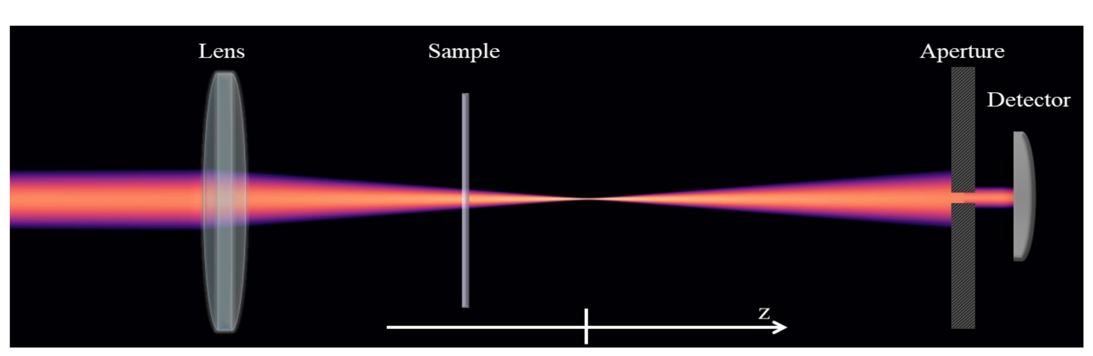
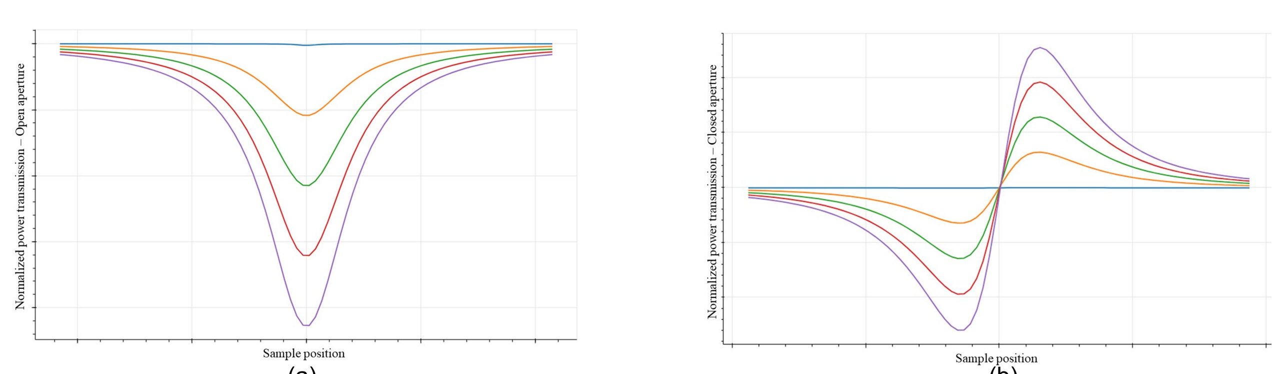


Figure 3: Schematic diagram of the optical system used for the Z-scan technique.



(a) (b)

Figure 4: Theoretical open-aperture Z-Scan results (a) and theoretical closed-aperture Z-Scan results (b).

Experimental Equipment

High-Power laser: The laser can be continuous-wave (CW) or pulsed, the requirement is that the power is high enough to excite the nonlinearities of the sample.

Figure 5: Femto-Second, pulsed laser from Menlo Labs.

Optical Elements: Depending on the laser, the detectors and the experimental protocol some filters should be used for controlled optical attenuation. In our implementation we used: a plano-convex spherical lens, several mirrors for facilitating optical alignment, and a rotating half-wave plate with a polarizing beam splitter to control light polarization state and incident power level.

(a) (b) (c) (d)

Figure 6: Optical Lens (a), Optical Mirror (b), Adjustable Iris (c) and Rotating Half-Wave Plate (d).

Prepared Mounted Sample: If solid crystals or glasses are characterized, their mounting is usually simple, and the sample preparation depends on the material synthesis method. The characterization of solids is usually made by direct exposition of the sample to the laser radiation. If liquids or gases are characterized, specialized cuvettes or chambers would be required.

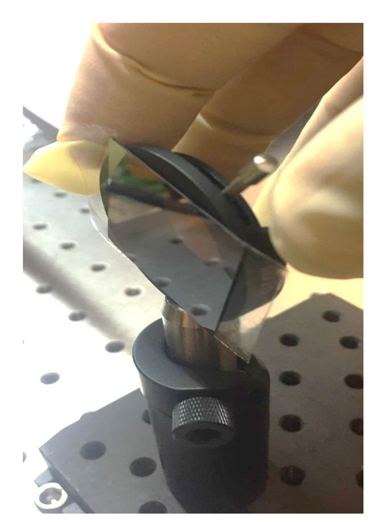


Figure 7: Mounted solid (silicon wafer) sample.

Optical Power-Meter: When implementing the Z-Scan technique, two kinds of measurement are needed: closed-aperture and open-aperture.

(a) (b)

Figure 8: Thorlabs Photodetector with USB connector (a), Photodetector connected to Thorlabs Optical Power Monitor Software (b).

Electronics: The data collected by the power-meter(s) must be processed to infer the nonlinear properties of the material under study. Thus, it must be transferred from the power meter(s) to a computerized system. Some power-meters have integrated software that will perform the direct conversion from electrical to optical variables.

Results

An open-source software has been developed for extracting the nonlinear properties, and some setup parameters, from experimental data (like the measurements illustrated in Fig. 9). It can be accessed from an online repository [23] (see QR code). The instructions to launch the program are also available in the repository. The data processing can be performed directly applying the theoretical framework derived by the team, which allows to analyze the input/output power relation and carry out a curve fitting.

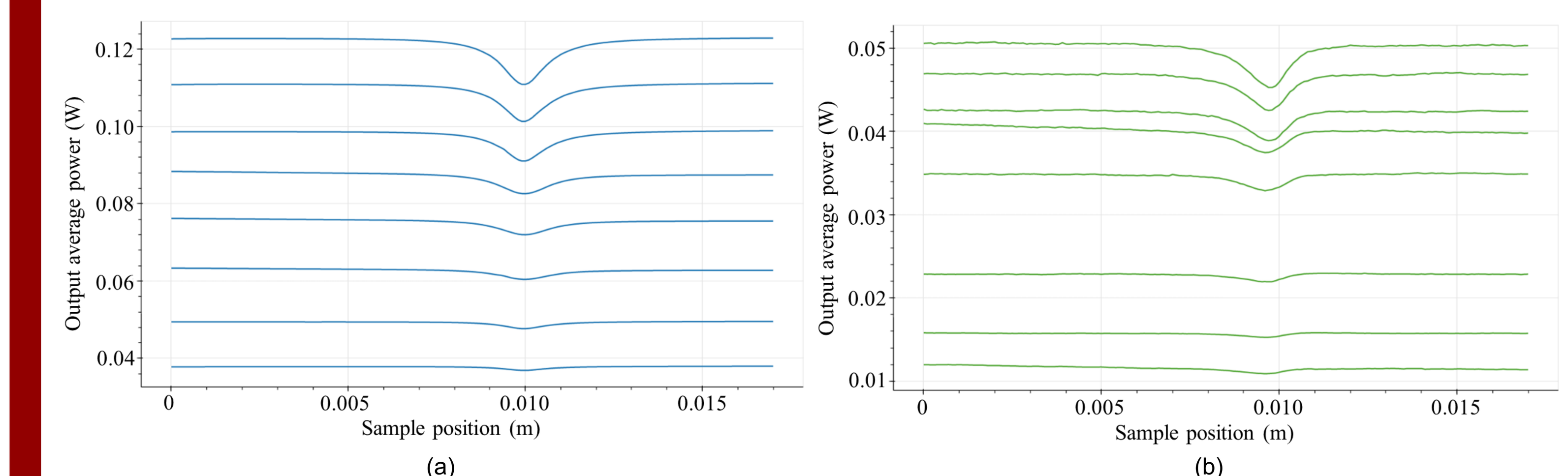


Figure 9: Open-aperture data, obtained from multiple Z-scans with different incident power levels (a) and closed-aperture data, obtained from multiple Z-scans with different incident power levels (b).

Curves in Fig. 10(a) have been arranged from the lower positions to the higher ones in order of increasing incident power, so it is possible to notice that as incident power increases, the peak-valley transmission difference increases as well. As the peak-valley transmission difference varies along with the incident power level, it may be understood as a function of input power. The derivative of this function is an indicator of how strong the nonlinear refractive response of the material is. This makes the derivative the quantity to extract from the experimental closed-aperture data. In the software, this is made by applying a linear regression on the set of experimental values.

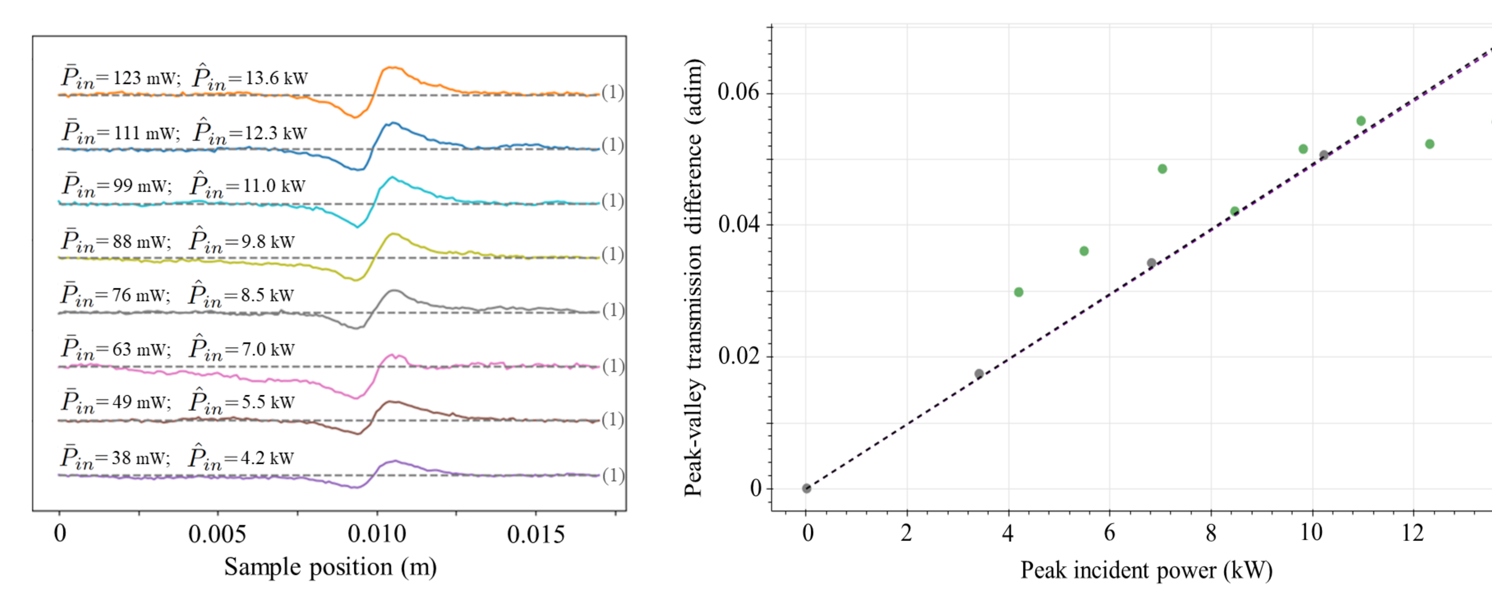


Figure 10: Normalized experimental closed-aperture curves, obtained as the quotient between the scaled closed-aperture and open-aperture curves (a) and superimposed scatter plot of the experimental (green dots) and simulated (gray dots) peak-valley transmission difference obtained from Z-scans with different incident power levels (b).

Table 2. Experimental Results.

Material	Silicon
β_{TPA}	24.6×10^{-12} m/W
n_2	5.69×10^{-18} m²/W
w_0	19.3 μm

Conclusion

Through this work, we offer an educational package tailor-made for undergraduate research in the field of nonlinear optics with the Z-Scan technique. We have demonstrated how to conduct this experiment, providing ample information regarding the experimental equipment necessary to carry out Z-Scan experiments in an undergraduate research setting. Through the appendices and online repository provided in the references (see Ref. 23, and QR codes), instructors and students should be able to take the results from their Z-Scan experiments and extract the data in order to determine the β_{TPA} and n_2 nonlinear constants present in tested samples (see table 2). Through the processes outlined in our work, we also show that the photonics laboratory at Bridgewater State University offers our services to potential academic and industry partners for the sampling of materials of interest in their research through our Z-Scan experimental setup.

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References

[1] Glick, M., Kimmerling, L. C., and Pfahl, R. C., "A roadmap for integrated photonics," Optics and Photonics News 29(3), 36–41 (2018).
[2] Minzioni, P., Lacava, C., Tanabe, T., Dong, J., Hu, X., Csaba, G., Porod, W., Singh, G., Willner, A. E., Almaiman, A., et al., "Roadmap on all-optical processing," Journal of Optics 21(6), 063001 (2019).
[3] Moody, G., Sorger, V. J., Blumenthal, D. J., Juodawlkis, P. W., Loh, W., Sorace-Agaskar, C., Jones, A. E., Balram, K. C., Matthews, J. C., Laing, A., et al., "2022 roadmap on integrated quantum photonics," Journal of Physics: Photonics 4(1), 012501 (2022).
[4] Pelucchi, E., Fagas, G., Aharonovich, I., Englund, D., Figueroa, E., Gong, Q., Hannes, H., Liu, J., Lu, C.-Y., Matsuda, N., et al., "The potential and global outlook of integrated photonics for quantum technologies," Nature Reviews Physics 4(3), 194–208 (2022).
[5] Metcalf, B. J., Spring, J. B., Humphreys, P. C., Thomas-Peter, N., Barbieri, M., Kolthammer, W. S., Jin, X.-M., Langford, N. K., Kundys, D., Gates, J. C., et al., "Quantum teleportation on a photonic chip," Nature photonics 8(10), 770–774 (2014).
[6] Spring, J. B., Metcalf, B. J., Humphreys, P. C., Kolthammer, W. S., Jin, X.-M., Barbieri, M., Datta, A., Thomas-Peter, N., Langford, N. K., Kundys, D., et al., "Boson sampling on a photonic chip," Science 339(6121), 798–801 (2013).
[7] Moille, G., Combrie, S., Morgenroth, L., Lehoucq, G., Neuilly, F., Hu, B., Decoster, D., and de Rossi, A., "Integrated all-optical switch with 10 ps time resolution enabled by ald," Laser & Photonics Reviews 10(3), 409–419 (2016).
[8] Hu, X.-M., Zhang, C., Liu, B.-H., Cai, Y., Ye, X.-J., Guo, Y., Xing, W.-B., Huang, C.-X., Huang, Y.-F., Li, C.-F., et al., "Experimental high-dimensional quantum teleportation," Physical Review Letters 125(23), 230501 (2020).
[9] Gomez, E. S., Gomez, S., Gonzalez, P., Cañas, G., Barra, J. F., Delgado, A., Xavier, G. B., Cabello, A., Kleinmann, M., Vertesi, T., et al., "Device-independent certification of a nonprojective qubit measurement," Physical review letters 117(26), 260401 (2016).
[10] Martınez, D., Tavakoli, A., Casanova, M., Canas, G., Marques, B., and Lima, G., "High-dimensional quantum communication complexity beyond strategies based on bell's theorem," Physical review letters 121(15),150504 (2018).
[11] Manufacturing USA, "Aim photonics (american institute for manufacturing integrated photonics)." https://www.manufacturingusa.com/institutes/aim-photonics (2022). Accessed: 26 July 2022.
[12] "National photonics initiative." https://www.lightourfuture.org/home/ (2022). Accessed: 26 July 2022.
[13] Hecht, Jeff, "Industrializing photonics - laser focus world." https://www.laserfocusworld.com/optics/article/14203511/industrializing-photonics (2021). Accessed: 26 July 2022.
[14] Manufacturing USA, "Attracting stem talent for careers in advanced manufacturing." https://www.manufacturingusa.com/studies/attracting-STEM-talent-careers-advanced-manufacturing (2022).
[15] Massachusetts Center for Advanced Manufacturing, "News." https://cam.masstech.org/news (2022). Accessed: 26 July 2022.
[16] "National quantum initiative." https://www.quantum.gov/ (2021). Accessed: 26 July 2022.
[17] Kirchain, R., Moore, E., Field, F. R., Saini, S., and Westerman, G., "Preparing the advanced manufacturing workforce: A study of occupation and skills demand in the photonics industry," (Feb 2021).
[18] Stegeman, G. I. and Seaton, C. T., "Nonlinear integrated optics," Journal of applied physics 58(12), R57–R78 (1985).
[19] Garmire, E., "Nonlinear optics in daily life," Optics express 21(25), 30532–30544 (2013).
[20] Petrella, J. K. and Jung, A. P., "Undergraduate research: Importance, benefits, and challenges," Interna-tional journal of exercise science 1(3), 91 (2008).
[21] Sheik-Bahae, M., Said, A. A., Wei, T. H., Hagan, D. J., and Stryland, E. V., "Sensitive measurement of optical nonlinearities using a single beam," IEEE J. Quantum Electron. 26(4), 760–769 (1990).
[22] Chapple, P., Staromlynska, J., and McDuff, R., "Z-scan studies in the thin-and the thick-sample limits," JOSA B 11(6), 975–982 (1994).
[23] Arango, J. J., "Z-scan: Parameter extraction program." Software in online repository: https://github.com/juanjosearango/z-scan-parameter-extraction-program (2022).
[24] Zhang, L., Agarwal, A. M., Kimerling, L. C., and Michel, J., "Nonlinear group IV photonics based on silicon and germanium: from near-infrared to mid-infrared," Nanophotonics 3(4-5), 247–268 (2014).
[25] Boyd, R. W., [Nonlinear optics], Academic Press (2020).
[26] Agrawal, G. P., "Nonlinear fiber optics," in [Nonlinear Science at the Dawn of the 21st Century], 195–211, Springer (2000).
[27] Mizuguchi, T. and Nuriya, M., "Applications of second harmonic generation (SHG)/sum-frequency generation (SFG) imaging for biophysical characterization of the plasma membrane," Biophysical Reviews 12(6), 1321–1329 (2020).
[28] Kumar, V., Coluccelli, N., and Polli, D., "Chapter 5 - coherent optical spectroscopy/microscopy and applications," in [Molecular and Laser Spectroscopy], Gupta, V., ed., 87–115, Elsevier (2018).
[29] Couteau, C., "Spontaneous parametric down-conversion," Contemporary Physics 59(3), 291–304 (2018).
[30] Keller, T. E. and Rubin, M. H., "Theory of two-photon entanglement for spontaneous parametric down-conversion driven by a narrow pump pulse," Physical Review A 56(2), 1534 (1997).
[31] Hill, K., Johnson, D., Kawasaki, B., and MacDonald, R., "CW three-wave mixing in single-mode optical fibers," Journal of Applied Physics 49(10), 5098–5106 (1978).
[32] Anwar, A., Perumangatt, C., Steinlechner, F., Jennewein, T., and Ling, A., "Entangled photon-pair sources based on three-wave mixing in bulk crystals," Review of Scientific Instruments 92(4), 041101 (2021).
[33] Dudley, J. M., Genty, G., and Coen, S., "Supercontinuum generation in photonic crystal fiber," Reviews of modern physics 78(4), 1135 (2006).
[34] Dudley, J. M. and Taylor, J. R., [Supercontinuum generation in optical fibers], Cambridge University Press (2010).
[35] Dashtban, Z., Salehi, M. R., and Abiri, E., "Supercontinuum generation in near-and mid-infrared spectral region using highly nonlinear silicon-core photonic crystal fiber for sensing applications," Photonics and Nanostructures-Fundamentals and Applications 46, 100942 (2021).
[36] Poudel, C. and Kaminski, C. F., "Supercontinuum radiation in fluorescence microscopy and biomedical imaging applications," JOSA B 36(2), A139–A153 (2019).
[37] Brosnan, S. and Byer, R., "Optical parametric oscillator threshold and linewidth studies," IEEE Journal of Quantum Electronics 15(6), 415–431 (1979).
[38] Barbier, M., Zaquine, I., and Delaye, P., "Generation of correlated photon pairs by spontaneous four-wave mixing in liquid-core microstructured fibres," in [2014 The European Conference on Optical Communication (ECOC)], 1–3, IEEE (2014).
[39] Fisher, R. A., [Optical phase conjugation], Academic press (2012).
[40] Saleh, B. E. and Teich, M. C., [Fundamentals of photonics], John Wiley & sons (2019).
[41] Sheik-Bahae, M., Said, A. A., and Stryland, E. W. V., "High-sensitivity, single-beam n2 measurements," Opt. Lett. 14(17), 955–957 (1989).

Software

Manuals