Post-2000 nonlinear optical materials and their characterization: data tables and best practices

Nathalie Vermeulen,[1] Daniel Espinosa,[2] Adam Ball,[3] John Ballato,[4] Philippe Boucaud,[5] Georges Boudebs,[6] Cecília L. A. V. Campos,[7] Peter Dragic,[8] Anderson S. L. Gomes,[7] Mikko J. Huttunen,[9] Nathaniel Kinsey,[3] Rich Mildren,[10] Dragomir Neshev,[11] Lázaro Padilha,[12] Minhao Pu,[13] Ray Secondo,[3] Eiji Tokunaga,[14] Dmitry Turchinovich,[15] Jingshi Yan,[11] Kresten Yvind,[13] Ksenia Dolgaleva,[2] and Eric W. Van Stryland[16]

(1) Vrije Universiteit Brussel, Brussels, Belgium
(2) University of Ottawa, Ottawa, Canada
(3) Virginia Commonwealth University, Richmond, USA
(4) Clemson University, Clemson, USA
(5) Université Côte d'Azur, Sophia-Antipolis, France
(6) Univ Angers, Angers, France
(7) Universidade Federal de Pernambuco, Recife, Brazil
(8) University of Illinois at Urbana-Champaign, Urbana, USA
(9) Tampere University, Tampere, Finland
(10) Macquarie University, Sydney, Australia
(11) Australian National University, Canberra, Australia
(12) Universidade Estadual de Campinas, Sao Paulo, Brazil
(13) Technical University of Denmark, Lyngby, Denmark
(14) Tokyo University of Science, Tokyo, Japan
(15) Universität Bielefeld, Bielefeld, Germany
(16) University of Central Florida, Orlando, USA

In its 60 years of existence, the field of nonlinear optics (NLO) has witnessed tremendous growth, and it has been gaining additional momentum over the past two decades thanks to major breakthroughs in materials science and technology. However, a data table providing an overview of these post-2000 developments in NLO has not yet been presented. Here, we introduce a new set of NLO data tables based on a representative collection of experimental works published since 2000 for different material categories (bulk materials, solvents, 0D-1D-2D materials, metamaterials, fiber waveguiding materials, on-chip waveguiding materials, hybrid waveguiding systems, and THz NLO materials) [1]. The data tables are mostly focused on experimental papers that not only provided NLO coefficients, but also reported experimental parameters that give the context and limits of validity for using the quoted coefficient values. In this regard, we decided to also include in our work a list of best practices for performing and reporting NLO experiments [1].

To build the data tables, we started by identifying the different material categories while also listing the different NLO techniques ('methods') and their associated best practices. We then performed a literature search for experimental papers on second- and third-order nonlinearities published since 2000 and made a selection based on the listed best practices. Finally, we filled out the data in dedicated table templates per material category. To minimize errors, the data provided by each co-author were also cross-checked by another co-author. A typical table layout is shown in Fig. 1. Our final work (>200 pages) [1] comprises 8 data tables for 8 material categories, with each table accompanied by an introductory text addressing relevant background information prior to 2000, as well as a discussion of the general trends seen in the data table (e.g., how the new post-2000 data represent an advancement) and some recommendations for future NLO research.

Notwithstanding the enormous growth in NLO publications since 2000, many of them were not taken up in the tables presented here as they provided too limited information to comply with the best practices. The papers that brought most value to the tables are those that report one or several NLO coefficients – and possibly also conversion efficiencies – for one or several materials, wavelengths, pulse durations, etc., measured and reported along the best practices. It is also key that papers clearly specify the material properties and fabrication details, and provide information on both the nonlinear and linear optical characteristics, such as the linear loss. We encourage the NLO community to take these aspects into account for future publications and to make use of the best practices listed in our work [1]. This will enable a more adequate comparison, interpretation and use of the published parameters, and as such further stimulate the overall progress in NLO science and applications.

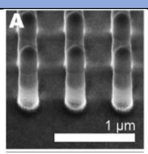
MATERIAL PROPERTIES		MEASUREMENT		NONLINEAR PROPERTIES			
Material Substrate Fabrication Thickness Crystallinity	SEM image	Method	Pump wavelength Peak irradiance Beam waist Pulse width Rep. rate	Conversion efficiency (% or W^{-1})	$\lvert\chi^{(2)}\rvert$ (m/V)	Enhancement mechanism	Reference
GaAs / AlGaO GaAs MBE/e-beam lith. 0.45 [µm] Monocryst. / monocryst.		SHG	1020 [nm] 3.4×10^{7} [MW/m^2] 3 [µm] 0.012 [ps] 80000 [kHz]	2×10^{-3} % / 1.5×10^{-8} W^{-1}	-	Magnetic dipole resonance	[Liu2016]

Fig. 1 Excerpt of the data table for metamaterials with a second-order nonlinearity [1].

[1] N. Vermeulen, D. Espinosa, A. Ball, J. Ballato, P. Boucaud, G. Boudebs, C. L. A. V. Campos, P. Dragic, A. S. L. Gomes, M. J. Huttunen, N. Kinsey, R. Mildren, D. Neshev, L. Padilha, M. Pu, R. Secondo, E. Tokunaga, D. Turchinovich, J. Yan, K. Yvind, K. Dolgaleva, and E. W. Van Stryland, "Post-2000 Nonlinear Optical Materials and Measurements: Data Tables and Best Practices," *Journal of Physics:Photonics* (2023 – in press). https://iopscience.iop.org/article/10.1088/2515-7647/ac9e2f

979-8-3503-4599-5/23/$31.00 ©2023 IEEE