

Air Photonics

Stefan Skupin

Institut Lumière Matière, UMR 5306 Université Lyon 1 - CNRS, Université de Lyon, 69622 Villeurbanne, France

Modern ultrashort laser sources routinely produce powerful enough pulses to ionize the ambient air, so that the very atmosphere we breath becomes an interesting medium for nonlinear photonics. One of the first and most prominent ultrafast nonlinear effects studied in air is filamentation [1,2], and so-called femtosecond filaments have enabled many applications, for example remote supercontinuum generation [3] or pulse compression [4,5], for review see [6,7]. Air lasing [8] offering exciting possibilities for standoff detection [9] has been demonstrated. Moreover, air is easily exploited as nonlinear medium in hollow-core photonic crystal fibers [10].

One of the most intriguing air photonics application is certainly the generation of broadband THz radiation in an air plasma produced by a two-color laser pulse composed of fundamental and its second harmonic frequency. First attributed to a four-wave mixing process [11], it is nowadays well established that photo currents in the laser generated plasma are responsible for the THz emission [12]. Spectral properties of the radiation produced can be understood by the local current (LC) model [13], and the elongated shape of the plasma favours forwards THz emission [14]. Several methods have been proposed to increase the THz energy yield of such laser-plasma based sources: Optimizing the pump waveform by employing, e.g., three pump colors [15], exploiting the scaling of the THz emission with the fundamental pump wavelength [16,17], or going beyond using linearly polarized pump pulses [18,19]. Another intriguing aspect of THz wave air photonics is that with air biased coherent detection (ABCD) [20] a broadband and robust THz detection scheme is available that is readily combined with the previously discussed source [21,22] to obtain a versatile THz platform.

References

- [1] A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, "Self-channeling of high-peak-power femtosecond laser pulses in air," *Opt. Lett.* **20**, 73-75 (1995).
- [2] M. Mlejnek, E. M. Wright, and J. V. Moloney, "Dynamic spatial replenishment of femtosecond pulses propagating in air," *Opt. Lett.* **23**, 382-384 (1998).
- [3] J. Kasparian, M. Rodríguez, G. Méjean, J. Yu, E. Salmon, H. Wille, R. Bourayou, S. Frey, Y.B. André, A. Mysyrowicz, and R. Sauerbrey, "White-light filaments for atmospheric analysis," *Science* **301**, 61-64 (2003).
- [4] C.P. Hauri, W. Kornelis, F.W. Helbing, A. Heinrich, A. Couairon, A. Mysyrowicz, J. Biegert, and U. Keller, "Generation of intense, carrier-envelope phase-locked few-cycle laser pulses through filamentation," *Appl. Phys. B* **79**, 673-677 (2004).
- [5] S. Skupin, G. Stibenz, L. Berge, F. Lederer, T. Sokollik, M. Schnürer, N. Zhavoronkov, and G. Steinmeyer, "Self-compression by femtosecond pulse filamentation: Experiments versus numerical simulations," *Phys. Rev. E* **74**, 056604 (2006).
- [6] A. Couairon and A. Mysyrowicz, "Femtosecond filamentation in transparent media," *Phys. Rep.* **441**, 47-189 (2007).
- [7] L. Bergé, S. Skupin, R. Nuter, J. Kasparian, and J.P. Wolf, "Ultrashort filaments of light in weakly ionized, optically transparent media," *Rep. Prog. Phys.* **70**, 1633 (2007).
- [8] A. Dogariu, J.B. Michael, M.O. Scully, and R.B. Miles, "High-gain backward lasing in air," *Science* **331**, 442-445 (2011).
- [9] Y. Fu, J. Cao, K. Yamamoto, and H. Xu, "Air-laser-based standoff coherent Raman spectrometer," *Ultrafast Science* **2022**, 9867028 (2022).
- [10] J. Luan, P.St.J. Russell, and D. Novoa, "Efficient self-compression of ultrashort near-UV pulses in air-filled hollow-core photonic crystal fibers," *Opt. Express* **29**, 13787-13793 (2021)
- [11] D. J. Cook and R. M. Hochstrasser, "Intense terahertz pulses by four-wave rectification in air," *Opt. Lett.* **25**, 1210-1212 (2000).
- [12] K.Y. Kim, A.J. Taylor, J.H. Glowina, and G. Rodríguez, "Coherent control of terahertz supercontinuum generation in ultrafast laser-gas interactions," *Nature Phot.* **2**, 605-609 (2008).
- [13] I. Babushkin, S. Skupin, A. Husakou, C. Köhler, E. Cabrera-Granado, L. Bergé, and J. Herrmann, "Tailoring terahertz radiation by controlling tunnel photoionization events in gases," *New J. Phys.* **13**, 123029 (2011).
- [14] C. Köhler, E. Cabrera-Granado, I. Babushkin, L. Bergé, J. Herrmann, and S. Skupin, "Directionality of terahertz emission from photoinduced gas plasmas," *Opt. Lett.* **36**, 3166-3168 (2011).
- [15] P. González de Alaiza Martínez, I. Babushkin, L. Bergé, S. Skupin, E. Cabrera-Granado, C. Köhler, U. Morgner, A. Husakou, and J. Herrmann, "Boosting Terahertz Generation in Laser-Field Ionized Gases Using a Sawtooth Wave Shape," *Phys. Rev. Lett.* **114**, 183901 (2015)
- [16] M. Clerici, M. Peccianti, B.E. Schmidt, L. Caspani, M. Shalaby, M. Giguère, A. Lotti, A. Couairon, F. Légaré, T. Ozaki, D. Faccio, and R. Morandotti, "Wavelength Scaling of Terahertz Generation by Gas Ionization," *Phys. Rev. Lett.* **110**, 253901 (2013).
- [17] A. Nguyen, K. J. Kaltenecker, J.-C. Delagnes, B. Zhou, E. Cormier, N. Fedorov, R. Bouillaud, D. Descamps, I. Thiele, S. Skupin, P. U. Jepsen, and L. Bergé, "Wavelength scaling of terahertz pulse energies delivered by two-color air plasmas," *Opt. Lett.* **44**, 1488-1491 (2019).
- [18] C. Meng, W. Chen, X. Wang, Z. Lü, Y. Huang, J. Liu, D. Zhang, Z. Zhao, and J. Yuan, "Enhancement of terahertz radiation by using circularly polarized two-color laser fields," *Appl. Phys. Lett.* **109**, 131105 (2016).
- [19] C. Tailliez, A. Stathopoulos, S. Skupin, D. Buožius, I. Babushkin, V. Vaičaitis, and L. Bergé, "Terahertz pulse generation by two-color laser fields with circular polarization," *New J. Phys.* **22**, 103038 (2020).
- [20] N. Karpowicz, J. Dai, X. Lu, Y. Chen, M. Yamaguchi, H. Zhao, X.-C. Zhang, L. Zhang, C. Zhang, M. Price-Gallagher, C. Fletcher, O. Mamer, A. Lesimple, and K. Johnson, "Coherent heterodyne time-domain spectrometry covering the entire terahertz gap," *Appl. Phys. Lett.* **92**, 011131 (2008).
- [21] B. Clough, J. Dai, X.-C. Zhang, "Laser air photonics: beyond the terahertz gap," *Materials Today* **15**, 50-58 (2012)
- [22] E. Prost, V. Lorient, E. Constant, I. Compagnon, L. Bergé, F. Lépine, and S. Skupin, "Air-photonics terahertz platform with versatile micro-controller based interface and data acquisition," *Rev. Sc. Inst.* **93**, 033004 (2022).