

Review of Microplasma's Use in Terahertz Technology

Kola Maruthi Vara Prasad¹ and Dr. Veeresh Kumar²
Research Scholar, Department of Physics¹
Assistant Professor, Department of Physics²
Sunrise University, Alwar, Rajasthan, India

Abstract: *Terahertz functional devices are essential for advanced terahertz radiation applications in biology, medicine, nanotechnology, and wireless communications. Due to its small size and high plasma frequency, the interaction between terahertz radiation and microplasma presents opportunities for developing functional terahertz devices. This article discusses the use of microplasma as terahertz generators, amplifiers, filters, and detectors. The advantages and drawbacks of transdisciplinary research using microplasma and terahertz technologies are underlined.*

Keywords: Microplasma, Terahertz, Applications

REFERENCES

- [1]. Liang, W.; Chao, T.; Zhu, S. Terahertz Time Domain Spectroscopy of Transformer Insulation Paper after Thermal Aging Intervals. *Materials* 2018, 11, 2124.
- [2]. Dhillon, S.S.; Vitiello, M.S.; Linfield, E.H.; Davies, A.G.; Hoffmann, M.C.; Booske, J.; Paoloni, C.; Gensch, M.; Weightman, P.; Williams, G.P.; et al. The 2017 terahertz science and technology roadmap. *J. Phys. D Appl. Phys.* 2017, 50, 043001.
- [3]. Siegel, P.H. Terahertz technology in biology and medicine. *IEEE Trans. Microw. Theory Tech.* 2004, 52, 2438–2447.
- [4]. Siegel, P.H. THz technology. *IEEE Trans. Microw. Theory Tech.* 2002, 50, 910–928.
- [5]. Shi, S.C.; Paine, S.; Yao, Q.J.; Lin, Z.H.; Li, X.X.; Duan, W.Y.; Matsuo, H.; Zhang, Q.; Yang, J.; Ashley, M.C.B.; et al. Terahertz and far-infrared windows opened at Dome A in Antarctica. *Nat. Astron.* 2016, 1, 1.
- [6]. Hangyo, M. Development and future prospects of terahertz technology. *Jpn. J. Appl. Phys.* 2015, 54, 1–16.
- [7]. Jepsen, P.U.; Cooke, D.G.; Koch, M. Terahertz spectroscopy and imaging—Modern techniques and applications. *Laser Photonics Rev.* 2011, 5, 1–43.
- [8]. Son, J.H.; Oh, S.J.; Cheon, H. Potential clinical applications of terahertz radiation. *J. Appl. Phys.* 2019, 125, 190901.
- [9]. Shen, Y.C.; Lo, T.; Taday, P.F. Detection and identification of explosives using terahertz pulsed spectroscopic imaging. *Appl. Phys. Lett.* 2005, 86, 377.
- [10]. Akyildiz, I.F.; Jornet, J.M.; Chong, H. Terahertz band: Next frontier for wireless communications. *Phys. Commun.* 2014, 12, 16–32.
- [11]. Mittleman, D.M. Twenty years of terahertz imaging. *Opt. Express* 2018, 26, 9417.
- [12]. Wang, B.; Cappelli, M.A. A tunable microwave plasma photonic crystal filter. *Appl. Phys. Lett.* 2015, 107, 199902.
- [13]. Ginzburg, V.L. *The Propagation of Electromagnetic Waves in Plasma*; Science Press: Beijing, China, 1978.
- [14]. Waldman, M.; Gordon, R.G. Generalized electron gas–Drude model theory of intermolecular forces. *J. Chem. Phys.* 1979, 71, 1340–1352.

- [15]. Sakai, O.; Tachibana, K. Plasmas as metamaterials: A review. *Plasma Sources Sci. Technol.* 2012, 21, 013001.
- [16]. Xu, L.L.; Tao, Z.Y.; Sang, T.Q. Thermally Tunable Narrow Band Filter Achieved by Connecting Two Opaque Terahertz Waveguides. *IEEE Photonics Technol. Lett.* 2017, 29, 869–872.
- [17]. Li, S.; Liu, H.; Sun, Q.; Huang, N.A. Tunable Terahertz Photonic Crystal Narrow-Band Filter. *IEEE Photonics Technol. Lett.* 2015, 27, 752–754.
- [18]. Xue, Q.W.; Wang, X.H.; Liu, C.L.; Liu, Y.W. Pressure-controlled terahertz filter based on 1D photonic crystal with a defectivesemi-conductor. *Plasma Sci. Technol.* 2018, 20, 035504.
- [19]. Federici, J.; Moeller, L. Review of terahertz and subterahertz wireless communications. *J. Appl. Phys.* 2010, 107, 6–323.
- [20]. Zhang, X.C.; Shkurinov, A.; Zhang, Y. Extreme terahertz science. *Nat. Photonics* 2017, 11, 16–18.
- [21]. Yu, J. Generation and Detection of Terahertz Signal. In *Broadband Terahertz Communication Technologies*; Springer: Singapore, 2021.
- [22]. Shur, M. Terahertz technology: Devices and applications. In *Proceedings of the 35th European Solid-State Device Research Conference, Grenoble, France, 16 September 2005*.
- [23]. Karpowicz, N.; Dai, J.; Lu, X.; Chen, Y.; Yamaguchi, M.; Zhao, H.; Zhang, X.-C. Coherent heterodyne time-domain spectrometry covering the entire "terahertz gap". *Appl. Phys. Lett.* 2008, 92, 011131.
- [24]. Liao, G.; Li, Y.; Zhang, Y. Demonstration of Coherent Terahertz Transition Radiation from Relativistic Laser-Solid Interactions. *Phys. Rev. Lett.* 2016, 116, 205003
- [25]. Vvedenskii, N.V.; Korytin, A.I.; Kostin, V.A. Two-Color Laser-Plasma Generation of Terahertz Radiation Using a Frequency-Tunable Half Harmonic of a Femtosecond Pulse. *Phys. Rev. Lett.* 2014, 112, 055004.
- [26]. Lu, X.; Zhang, X.C. Generation of Elliptically Polarized Terahertz Waves from Laser-Induced Plasma with Double Helix Electrodes. *Phys. Rev. Lett.* 2012, 108, 123903
- [27]. de Alaiza Martínez, P.G.; Babushkin, I.; Bergé, L.; Skupin, S.; Cabrera-Granado, E.; Köhler, C.; Morgner, U.; Husakou, A.; Herrmann, J. Boosting Terahertz Generation in Laser-Field Ionized Gases Using a Sawtooth Wave Shape. *Phys. Rev. Lett.* 2015, 114, 183901.
- [28]. Matsubara, E.; Nagai, M.; Ashida, M. Ultrabroadband coherent electric field from far infrared to 200 THz using air plasma induced by 10 fs pulses. *Appl. Phys. Lett.* 2012, 101, 021105.
- [29]. Hamster, H.; Sullivan, A.; Gordon, S. Subpicosecond, electromagnetic pulses from intense laser-plasma interaction. *Phys. Rev. Lett.* 1993, 71, 2725.
- [30]. Cook, D.J.; Hochstrasser, R.M. Intense terahertz pulses by four-wave rectification in air. *Opt. Lett.* 2000, 25, 1210–1212.
- [31]. Buccheri, F.; Zhang, X.C. Terahertz emission from laser-induced microplasma in ambient air. *Optica* 2015, 2, 366–369.
- [32]. Liu, K.; Buccheri, F.; Zhang, X.C. Terahertz science and technology of micro-plasma. *Physics* 2015, 44, 6
- [33]. Zhang, X.C.; Buccheri, F. Terahertz photonics of microplasma and beyond. *Lith. J. Phys.* 2018, 58, 248–256.
- [34]. Chen, M.; Yuan, X.; Sheng, Z. Scalable control of terahertz radiation from ultrashort laser-gas interaction. *Appl. Phys. Lett.* 2012 101, 161908.
- [35]. Ding, W.J.; Sheng, Z.M. Sub GV/cm terahertz radiation from relativistic laser-solid interactions via coherent transition radiation. *Phys. Rev. E* 2016, 93, 063204.
- [36]. Wu, H.C.; Sheng, Z.M.; Dong, Q.L. Powerful terahertz emission from laser wakefields in inhomogeneous magnetized plasmas. *Phys. Rev. E* 2007, 75, 016407.
- [37]. Thiele, I.; Martínez, P.G.D.A.; Nuter, R. Broadband terahertz emission from two-color femtosecond-laser-induced microplasmas. *Phys. Rev. A* 2017, 96, 053814.

- [38]. Liu, K.; Koulouklidis, A.D.; Papazoglou, D.G. Enhanced terahertz wave emission from air-plasma tailored by abruptly autofocusing laser beams. *Optica* 2016, 3, 605–608.
- [39]. Thiele, I.; Zhou, B.; Nguyen, A. Terahertz emission from laser-driven gas plasmas: A plasmonic point of view. *Optica* 2018, 5, 1617–1622.
- [40]. Deal, W.R. Solid-state amplifiers for terahertz electronics. In Proceedings of the 2010 IEEE MTT-S International Microwave Symposium, Anaheim, CA, USA, 23–28 May 2010; pp. 1122–1125.
- [41]. Tucek, J.C.; Basten, M.A.; Gallagher, D.A.; Kreischer, K.E. Testing of a 0.850 THz vacuum electronic power amplifier. In Proceedings of the 2013 IEEE 14th International Vacuum Electronics Conference (IVEC), Paris, France, 21–23 May 2013; pp. 1–2.
- [42]. Dai, J.; Xie, X.; Zhang, X.C. Terahertz wave amplification in gases with the excitation of femtosecond laser pulses. *Appl. Phys. Lett.* 2007, 91, 211102.
- [43]. Bogatskaya, A.V.; Volkova, E.A.; Popov, A.M. Plasma channel produced by femtosecond laser pulses as a medium for amplifying electromagnetic radiation of the subterahertz frequency range. *Quantum Electron.* 2013, 43, 1110.
- [44]. Bogatskaya, A.V.; Volkova, E.A.; Popov, A.M. On the possibility of a short subterahertz pulse amplification in a plasma channel created in air by intense laser radiation. *J. Phys. D Appl. Phys.* 2014, 47, 185202.
- [45]. Bogatskaya, A.V.; Gnezdovskaia, N.E.; Volkova, E.A. The role of plasma kinetics in the process of THz pulses generation and amplification. *Plasma Sources Sci. Technol.* 2020, 29, 105016.
- [46]. Tabib-Azar, M.; Fawole, O.C.; Pandey, S.S. Microplasma traveling wave terahertz amplifier. *IEEE Trans. Electron. Devices* 2017, 64, 3877–3884.
- [47]. Zhang, H.F.; Liu, S.B.; Kong, X.K. The properties of photonic band gaps for three-dimensional plasma photonic crystals in a diamond structure. *Phys. Plasmas* 2013, 20, 042110.
- [48]. Guo, B.; Xie, M.Q.; Peng, L. Photonic band structures of one-dimensional photonic crystals doped with plasma. *Phys. Plasmas* 2012, 19, 072111.
- [49]. Zhang, L.; Ouyang, J.T. Experiment and simulation on one-dimensional plasma photonic crystals. *Phys. Plasmas* 2014, 21, 103514.
- [50]. Fan, W.; Zhang, X.; Dong, L. Two-dimensional plasma photonic crystals in dielectric barrier discharge. *Phys. Plasmas* 2010, 17, 113501.
- [51]. Askari, N.; Mirzaie, R.; Eslami, E. Analysis of band structure, transmission properties, and dispersion behavior of THz wave in one-dimensional parabolic plasma photonic crystal. *Phys. Plasmas* 2015, 22, 112117.
- [52]. Qu, C.; Tian, P.; Semnani, A. Properties of arrays of microplasmas: Application to control of electromagnetic waves. *Plasma Sources Sci. Technol.* 2017, 26, 105006.
- [53]. Shuqun, W.; Yuxiu, C.; Minge, L. Numerical study on the modulation of THz wave propagation by collisional microplasma photonic crystal. *Plasma Sci. Technol.* 2020, 22, 115402.
- [54]. Paliwoda, M.C.; Rovey, J.L. Multiple parameter space bandgap control of reconfigurable atmospheric plasma photonic crystal. *Phys. Plasmas* 2020, 27, 023516.
- [55]. Wang, Y.; Liu, S.; Zhong, S. Tunable multichannel terahertz filtering properties of dielectric defect layer in one-dimensional magnetized plasma photonic crystal. *Opt. Commun.* 2020, 473, 125985.
- [56]. Sakaguchi, T.; Sakai, O.; Tachibana, K. Photonic bands in two-dimensional microplasma arrays. II. Band gaps observed in millimeter and subterahertz ranges. *J. Appl. Phys.* 2007, 101, 073305.
- [57]. Yang, H.J.; Park, S.J.; Eden, J.G. Narrowband attenuation at 157 GHz by a plasma photonic crystal. *J. Phys. D Appl. Phys.* 2017, 50, 43–50.
- [58]. Yao, J.; Yuan, C.; Li, H. 1D photonic crystal filled with low-temperature plasma for controlling broadband microwave transmission. *AIP Adv.* 2019, 9, 065302.
- [59]. Sun, P.P.; Zhang, R.; Chen, W. Dynamic plasma/metal/dielectric photonic crystals in the mm-wave region: Electromagnetically-active artificial material for wireless communications and sensors. *Appl. Phys. Rev.* 2019, 6, 041406.

- [60]. Rogalski, A. History of infrared detectors. *Opto-Electron. Rev.* 2012, 20, 279–308.
- [61]. Park, S.G.; Melloch, M.R.; Weiner, A.M. Comparison of terahertz waveforms measured by electro-optic and photoconductive sampling. *Appl. Phys. Lett.* 1998, 73, 3184–3186
- [62]. Dai, J.; Xie, X.; Zhang, X.C. Detection of broadband terahertz waves with a laser-induced plasma in gases. *Phys. Rev. Lett.* 2006,
- [63]. Liu, J.; Zhang, X.C. Terahertz-radiation-enhanced emission of fluorescence from gas plasma. *Phys. Rev. Lett.* 2009, 103, 235002.
- [64]. Clough, B.; Liu, J.; Zhang, X.C. Laser-induced photoacoustics influenced by single-cycle terahertz radiation. *Opt. Lett.* 2010, 35, 3544–3546.
- [65]. Clough, B.; Liu, J.; Zhang, X.C. “All air–plasma” terahertz spectroscopy. *Opt. Lett.* 2011, 36, 2399–2401. Hou, L.; Shi, W.; Chen, S. Terahertz continuous wave detection using weakly ionized plasma in inert gases. *IEEE Electron. Device Lett.* 2013, 34, 689–691.
- [66]. Hou, L.; Han, X.; Shi, W. Detecting terahertz waves using microplasma array. In *Proceedings of the 2016 IEEE International Conference on Plasma Science (ICOPS)*, Banff, AB, Canada, 19–23 June 2016.
- [67]. Kim, K.Y.; Glowina, J.H.; Taylor, A.J. Terahertz emission from ultrafast ionizing air in symmetry-broken laser fields. *Opt. Express* 2007, 15, 4577–4584.
- [68]. Li, N.; Bai, Y.; Miao, T. Revealing plasma oscillation in THz spectrum from laser plasma of molecular jet. *Opt. Express* 2016, 24, 23009–23017.
- [69]. Debayle, A.; Gremillet, L.; Berge, L. Analytical model for THz emissions induced by laser-gas interaction. *Opt. Express* 2014, 22, 13691–13709.
- [70]. Du, H.; Chen, M.; Sheng, Z. THz emission control by tuning density profiles of neutral gas targets during intense laser-gas interaction. *Appl. Phys. Lett.* 2012, 101, 18111318.
- [71]. Sheng, Z.M.; Mima, K.; Zhang, J. Emission of electromagnetic pulses from laser wakefields through linear mode conversion. *Phys. Rev. Lett.* 2005, 94, 0950039.
- [72]. Liao, G.Q.; Li, Y.T.; Li, C. Bursts of Terahertz Radiation from Large-Scale Plasmas Irradiated by Relativistic Picosecond Laser Pulses. *Phys. Rev. Lett.* 2015, 114, 25500125.
- [73]. Kemp, A.J.; Pfund, R.; Meyer-Ter-Vehn, J. Modeling ultrafast laser-driven ionization dynamics with Monte Carlo collisional particle-in-cell simulations. *Phys. Plasmas* 2004, 11, 5648–5657.
- [74]. Babushkin, I.; Kuehn, W.; Khler, C. Ultrafast Spatiotemporal Dynamics of Terahertz Generation by Ionizing Two-Color Femtosecond Pulses in Gases. *Phys. Rev. Lett.* 2010, 105, 053903.