

THz Electromagnetic Metamaterials

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Electromagnetic metamaterials (EM³) are engineered composite materials that exhibit the peculiar property of their permittivity ϵ and permeability μ becoming simultaneously negative within a narrow frequency band. Such materials were introduced and analysed theoretically by Veselago [1] with stunning results such as a negative refractive index. After 30 years of dormancy, the field of EM³ has seen a strong surge in the past decade due to the design of the split ring resonator as one of the building blocks by Pendry et al. [2,3]. His theoretical results were quickly turned into experiments in the microwave range up to 11.2 GHz [4,5]. In 2005, some of the above authors published the first micromanufactured full EM³ [6]. Other groups have been investigating the magnetic resonance behaviour of micro/nanofabricated structures [7,8].

The objective is to achieve EM³ function at higher frequencies than GHz, i.e., in the THz range, the near infrared and the visible. This would allow applying the concept of sub-wavelength resolution imaging as worked out by Pendry and coworkers [9,10] directly to the visible spectral range.

SSLS has built and characterized EM³ based on the rod-split-ring design up to a record frequency of 216 THz [11-14]. The patterns were generated by both, laser direct writing and e beam writing, and partially used for X-ray lithography. To cover the two orders of magnitude in frequency range, the outer/inner diameter of the split rings had to be varied from 85/14 μm to 700/90 nm. For process reasons, the thickness was 14 μm for the microfabricated EM³ and 30 nm for the nanofabricated ones. Sample size was 2.1 \times 2.1 mm² for the earlier samples and is now 4.2 \times 4.2 mm².

EM³ built thus far at SSLS were planar structures that exhibit an anisotropic response to an incident wave field. In order to reduce such anisotropy, doubly inclined split ring arrays are being developed by means of tilted X-ray lithography in SU-8 resist [11,15]. Latest results and an outlook to future work will be given.

[1] V. G. Veselago, Sov. Phys. Usp. **10**, 509 (1968).

[2] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, Phys. Rev. Lett. **76**, 4773 (1996).

[3] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999).

[4] D.R. Smith, W.J. Padilla, D.C. Vier, S.C. Nemat-Nasser, S. Schultz, Phys. Rev. Lett. **84**(18), 4184 (2000).

[5] R.A. Shelby, D.R. Smith, S.C. Nemat-Nasser, S. Schultz, Appl. Phys. Lett. **78**(4), 489 (2001).

[6] H. O. Moser, B. D. F. Casse, O. Wilhelmi, and B. T. Saw, Phys. Rev. Lett. **94**, 063901 (2005).

[7] T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov, and X. Zhang, Science **303**, 1494 (2004).

[8] S. Linden, C. Enkrich, M. Wegener, J. Zhou, T. Koschny, and C. M. Soukoulis, Science **306**, 1351 (2004).

[9] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).

[10] J.B. Pendry, S.A. Ramakrishna, J. Phys.: Condens. Matter **15**, 6345(2003)

[11] H. O. Moser, B. D. F. Casse, O. Wilhelmi, and B. T. Saw, "Electromagnetic Metamaterials over the whole THz range — achievements and perspectives, Proceedings of the ICMAT 2005 Symposium R (Electromagnetic Materials)," World Scientific, Singapore, 2005, pp. 55–58, ISBN 981-256-411-X(pbk).

[12] B. D. F. Casse, H. O. Moser, O. Wilhelmi, and B. T. Saw, "Micro- and Nano-Fabrication of Electromagnetic Metamaterials for the Terahertz range, Proceedings of the ICMAT 2005 Symposium R (Electromagnetic Materials)," World Scientific, Singapore, 2005, pp. 18–25, ISBN 981-256-411-X(pbk).

[13] B. D. F. Casse, H. O. Moser, M. Bahou, L. K. Jian, P. D. Gu, "NanoElectromagnetic Metamaterials Approaching Telecommunication Frequencies", NanoSingapore 2006, 2006 IEEE Conference on Emerging Technologies — Nanoelectronics, pp 328–331, ISBN 0-7803-9357-0, Singapore 2006.

[14] B. D. F. Casse, H. O. Moser, L. K. Jian, M. Bahou, O. Wilhelmi, B. T. Saw, and P. D. Gu, Journal of Physics: Conference Series **34**, 885–890 (2006).

[15] B.D.F. Casse, Thesis, 2006, unpublished.