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Artificial materials for terahertz frequency applications

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Summary for a general audience

Over a hundred years ago scientists realised that visible light was part of the electromagnetic spectrum. The colours in the rainbow correspond to various wavelengths around a half millionth of a metre. In time, other types of electromagnetic radiation (emr) were recognized, e.g.: infrared (wavelength around a millionth of a metre) and microwaves (wavelength a centimetre or so). It was recognized that emr consists of both electric and magnetic fields moving along at a characteristic speed. The speed at which they travel inside a material is governed by an important property called the refractive index. A source of emr could be, e.g., a light bulb, or a radio antenna. Normally, we are not interested in getting close to a source of emr, but instead make use of the far-field, as it is called, where energy is carried away. Recently, it has been realised that there is a great deal happening close to the source, i.e. in the near-field. This project has dealt with specially-made devices that can manipulate this near-field in a certain wavelength range. This wavelength range lies between radio and infrared, and corresponds to wavelengths about one millimetre to about one thirtieth of a millimetre. It is also known as the terahertz (THz) range, because the frequency of oscillation of the electric and magnetic fields is about one million million times a second. This radiation can sense cancers and explosives because molecules wobble, vibrate and rotate at THz frequencies.

During the course of this project we have designed, built and measured the properties of artificial materials. In these materials, the refractive index can be engineered to make filters, special lenses that can produce "perfect" images and also, perhaps, new types of devices to transport emr into and out of hard-to-reach locations (e.g. inside of the human body). Typically, these materials consist of a "forest" of elements (e.g. cylindrical pillars) that are made of an insulating material or a metal. The key feature is that the size of the structures, and their separation, are around the same size as the wavelength of the emr concerned. The structures may also have to be organized in a special way, or be placed around holes in semiconductors or metals or other materials. For terahertz radiation, we are dealing with cylinders of several tens of micrometres in diameter and similar separation. We make these using the "photoresist" procedures developed by the semiconductor industry. Other types of artificial materials can be made by making repeated holes of special design in appropriate materials. At the end of the project, we have:

- Designed artificial material structures using various theoretical techniques (e.g. plane wave photonic band structure and finite difference time domain methods).
- Devised novel methods for fabricating the structures by special semiconductor techniques (such as ultraviolet based SU8 micromachining).
- Built artificial materials, such as pillar arrays, square and round holes etched in semiconductors, and metallic structures with arrays of grooves.
- Measured the way that such structures transmit terahertz emr, and have developed filters with exceptional properties, including filters that select particular wavelengths with great accuracy or which are built on polymer bases and can be tuned mechanically.

- Developed "super transmitters" that let through far more emr than would be expected and will be valuable for building terahertz microscopes.
- Have shown that we can observe, for the first time at terahertz frequencies, negative refraction (i.e. the terahertz beam is bent "the wrong way");
- Shown that we can create special thin (non-diffractive) beams of terahertz emr that could be used to make a functioning terahertz microscope.
- Made a number of technical advances, such as predicting and observing so called Tamm plasmon-polaritons.

Dissemination of research results

Journal papers

1. “Complex photonic band structure and effective plasma frequency of a two-dimensional array of metal rods”, S. Brand, R.A. Abram, M.A. Kaliteevski, *Physical Review B* **75** 035102 (2007)

2. “Terahertz frequency bandpass filters”, A.J.Gallant, M.A. Kaliteevski, S. Brand, D. Wood, M.C. Petty, R.A. Abram and J.M. Chamberlain, *Journal of Applied Physics* **102** 023102 (2007)

3. “Tamm plasmon-polaritons; possible electromagnetic states at the interface of a metal and a dielectric Bragg mirror”, M.A. Kaliteevski, I. Iorsh, S. Brand, R.A. Abram, J.M. Chamberlain, A.V. Kavokin and I.A. Shelykh, *Physical Review B* **76** 165415 (2007)

4. “Passband filters for terahertz radiation based on dual metallic photonic structures”, A.J. Gallant, M.A. Kaliteevski, D. Wood, M.C. Petty, R.A. Abram, S. Brand, G.P. Swift, D.A. Zeze and J.M. Chamberlain, *Applied Physics. Letters* **91** 161115 (2007)

5. “Effect of longitudinal excitations on surface plasmons”, M.A. Kaliteevski, S. Brand, J.M. Chamberlain and R.A. Abram and V.V. Nikolaev, *Solid State Communications.* **144** 413-417 (2007)

6. “Whispering gallery polaritons in cylindrical cavities”, M.A. Kaliteevski, S. Brand, R.A. Abram, A.V. Kavokin and L.S. Dang, *Physical Review B* **75** 233309 (2007)

7. “Interface photonic states at the boundary between a metal and a dielectric Bragg mirror”, I.A. Shelykh, M.A. Kaliteevskii, A.V. Kavokin, S. Brand, R.A. Abram, J.M. Chamberlain and GMalpuech, *Physica Status Solidi A - Applications and Materials Science* **204** 522-525 (2007)

8. “Tamm plasmon-polaritons: Possible electromagnetic states at the interface of a metal and a dielectric Bragg mirror”, M.A. Kaliteevski, I. Iorsh, S. Brand, R.A. Abram, J.M. Chamberlain, A.V. Kavokin and I.A. Shelykh, *Physical Review B* **76** 165415 (2007)

9**.** “Terahertz filter based on refractive properties of a metallic photonic crystal”, M.A. Kaliteevski, S. Brand, J. Garvie-Cook, R.A. Abram and J.M. Chamberlain, *Optics Express* **16** 7330-7335 (2008)

10. “Tamm plasmon-polaritons: slow and spatially compact light”, M.E. Sasin, R.P. Seisyan, M.A. Kaliteevski, S. Brand, R.A. Abram, J.M. Chamberlain, A.Yu.Egorov, A.P.Vasil’ev , V.S. Mikhrin and A.V. Kavokin, *Applied Physics Letters* **92** 251112 (2008)

11. “Negative refraction can make non-diffracting beams”, M.A. Kaliteevski, S. Brand, R.A. Abram, A.J. Gallant and J.M. Chamberlain. *Optics Express* **16** 14582-14587 (2008)

Conference papers

1. “Enhanced THz transmission through micromachined sub-wavelength annular apertures”, A.J. Gallant, J.A. Levitt, M. Kaliteevski, D. Wood, M.C. Petty, R.A. Abram, S. Brand and J.M. Chamberlain, IEE Seminar on MEMS Sensors & Actuators, London, UK, April 27-28, 2006, pp.171-175

2. "Enhanced THz transmission apertures through sub-wavelength annular apertures", A.J. Gallant, J.A. Levitt, M. Kaliteevski, D. Wood, M.C. Petty, R.A. Abram, S. Brand and J.M. Chamberlain, *Proc. SPIE* **6323** San Diego CA, 13-17 Aug 2006 (Paper 6323-16)

3. “THz frequency studies of metallic structures”, S. Brand, M.A. Kaliteevski, R.A. Abram, Proc. SPIE, 6328 San Diego CA, 13-17 Aug 2006 (Paper 63280L)

4. 'The Fabrication of High Aspect Ratio THz Metamaterials', A.J. Gallant, D. Wood, J A. Levitt, M.A. Kaliteevski, M.C. Petty, S. Brand, R.A. Abram and J.M. Chamberlain, Proc. IET Seminar on Metamaterials for Microwave and (Sub)Millimetrewave Applications, London, 19 September 2006, pp 117-120

5. "The fabrication of THz photonic filters using ultraviolet-based SU8 micromachining", A.J. Gallant, J.A. Levitt, G.P. Swift, D.C. Dai, M.A. Kaliteevski, D. Wood, M.C. Petty and J.M. Chamberlain, Proceedings of the 31st Joint International Conference of Infrared and Millimeter Waves and the 14th IEEE Terahertz Electronics Conference, Shanghai, September 2006. Eds. S.C.Shen, W.Lu, J. Zhang and W.B.Dou. page 194 . ISBN 1-4244-0399-5. IEEE Catalog: 06EX1385

6. “Artificial plasmonic materials for THz applications”, A.J. Gallant, J.A. Levitt, M.A. Kaliteevski, D. Wood, M.C. Petty, R.A. Abram, S. Brand, G.P. Swift, D.A. Zeze and J.M. Chamberlain, Photonics West 2007, *Proc. SPIE* **6472**, 647206 (2007)

7. “Micromachining for terahertz artificial materials”, A.J. Gallant, G.P. Swift, D.C. Dai, M.A. Kaliteevski, D.A. Zeze, D. Wood, M.C. Petty, S. Brand, R.A. Abram and J. M. Chamberlain, *MRS Proc.* **1016** Paper 1016- CC05-07

8. “Flexible polymer-based artificial materials for terahertz applications”, A.J. Gallant, D. Zeze, D.A. Wood, M.C. Petty, D.C. Dai and J M. Chamberlain, Proceedings of the Joint 32nd Infrared and Millimetre Waves and 15th IEEE International Terahertz Electronics Conference. Eds: M.J.Griffin et al., IEEE Catalog number 07EX1863, ISBN: 1-4244-1438-5 Page 962.

9. “Can micromachining help us to fill the terahertz gap?”, A..J.Gallant, (invited plenary) Proceedings of MEMSWAVE 2008, Crete, June 2008, in press

10. “Negative refracting materials at THz frequencies”, G. Peter Swift, Andrew J. Gallant , DeChang Dai, Mikhail A. Kaliteevski, Stuart Brand, Dagou A. Zeze , David Wood , Michael C. Petty , Richard A. Abram and J. Martyn Chamberlain . Proceedings of the 33rd International Conference on Infrared, Millimeter, and Terahertz Waves, California Institute of Technology, September 2008.

11. “Micromachined terahertz waveguides with embedded metal rods”, Andrew Gallant, Adam Baragwanath, Peter Swift, David Wood and Martyn Chamberlain . Proceedings of the 33rd International Conference on Infrared, Millimeter and Terahertz Waves, California Institute of Technology, September 2008.