National Textile Center

FY 2004 New Project Proposal

Project No.

M04-GT19s

Competency: Materials

Terahertz Properties of Textiles: Metamaterials, Sensors, and Security

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Objective:

This project will expand knowledge of electromagnetic-textile interactions in the range 500 GHz to 10 THz, i.e., in the wavelength range ~30 μm-1 mm. This knowledge will be used to enable new classes of terahertz (THz) materials and chemical sensors. THz metamaterials (MM's) will be fabricated by the selective incorporation of metal structures into yarns. The resulting textiles can form THz optical elements. Textile-based sensors will exploit these MM's as well as photonic-crystal (PC) effects, which are expected to be significant in the THz range. Such sensors may provide a low-cost alternative for chemical-sensing applications, and can be incorporated into clothing for military and civilian protection, and may in the future interface with THz wireless local area nets.

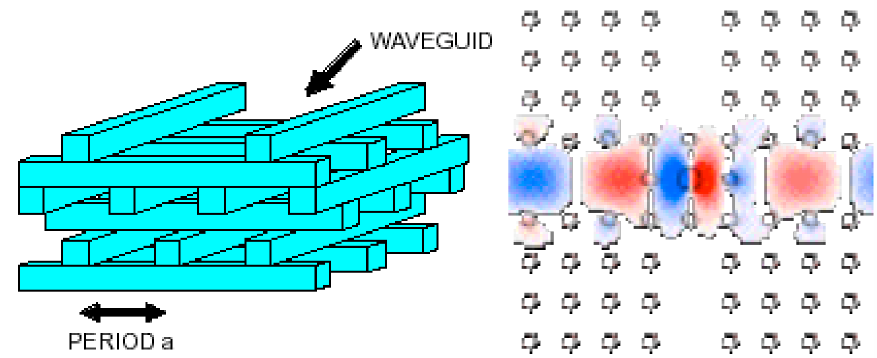
Relevance to NTC Mission:

Recent work is opening the THz region of the spectrum to industrial, medical, scientific, and military use. Most applications in the near term will be in spectroscopy (sensing) and imaging. The application of THz to textiles is *an entirely unexploited area*, and as such may provide new military and civilian markets, new process-monitoring tools for the industry, as well as a knowledge base for the emerging THz-imaging field. Possible new products include clothing that incorporates bio/chem-sensing functions and THz stealth clothing—clothing to counter THz imaging. THz functional textiles may also in the future be interfaced with THz wireless local area nets. This research impacts the creation of high-valued markets for textiles relying on technological areas where the US presently enjoys an advantage over the rest of the world, as well as to bulwark efforts at homeland security. Graduate and undergraduate students will be trained in areas at the interface of textile science, electrical engineering, physics, and chemistry.

State of the Art:

In the electromagnetic spectrum, between microwaves and mid-infrared light lies the THz regime—from ~500 GHz to 10 THz, corresponding to wavelengths from 30 μm to 1 mm. The THz regime has been under-exploited compared with the microwaves and infrared due to the failure of standard microwave techniques above ~100 GHz and of optical techniques below ~30 THz; however, in the last decade, substantial progress has been made in sources and receivers. This effort has been provided impetus in part by the significant spectroscopic signatures in the THz range of a number of small and of large molecules. For example, ammonia, carbon dioxide, and water all have strong vibrational or rotational modes in this range, attracting interest for THz-based environmental monitoring. At somewhat larger sizes, energetic materials (explosives) may have unique spectroscopic signatures in the THz range. And at even larger molecular weights, there is interest in possible spectroscopic fingerprinting of DNA by species for sensing of biological systems. In many of these cases, alternative approaches, such as Raman sensing, are not feasible due to the proximity of the Raman-shifted line to the laser frequency. Direct THz sensing may thus circumvent difficulties encountered with other means. THz spectroscopy and sensing of DNA is currently carried out by at least three research groups worldwide. In most cases, DNA is amplified and dry or jelled DNA samples are prepared. The propagation of a short pulse of THz radiation along a transmission line is monitored; the transmission depending on the presence or absence of a DNA sample within the transmission line is studied [1-3].

High sensitivity to very small quantities of agents to be detected is desired. For example, only ~100 or possibly ~10 anthrax spores may lead to the development of the disease in an individual, but sensing at low levels is likely to be difficult. One approach pursued in the Project Team Leader's group is the use of PC's fabricated in silicon to enhance the interaction of THz electromagnetic fields with low-concentration chemical agents. The structure consists of a silicon wafer in which an array of air holes is fabricated (hexagonal lattice) with a ~100 μm periodicity (spacing). In a frequency band near 1 THz, a photonic bandgap can be formed, i.e., a range of frequencies where propagation of electromagnetic waves is not supported. By making one row of air holes slightly larger than the surrounding ones or by omitting them, it is possible to propagate electromagnetic waves whose frequency lies in the photonic bandgap of the rest of the structure, thus leading to a waveguide action (similar structure in Fig. 1). In a structure with enlarged air holes in the waveguide, for electromagnetic waves of frequency slightly below the top of the bandgap (i.e., in the air band of the surrounding PC), the electromagnetic field associated with propagation in the waveguide is strongly enhanced in the air holes. This field enhancement can be exploited to increase the sensitivity to small quantities of agents in the air holes. Preliminary results obtained by the Project Team Leader's research group based on electromagnetic simulations show enhancements in the sensitivity compared with in free space by an order of magnitude. Similar effects are expected in other designs, e.g., the leftmost frame of Fig. 1.



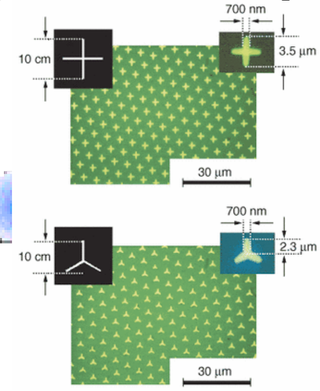


Fig. 1 (Left two frames): (Left) "Lincoln Log" PC from stacked dielectric rods [4]. (Middle) Air holes are etched in a silicon substrate in a hexagonal lattice. Row of omitted air holes that is larger than the others acts as a waveguide [5].
Fig. 2 (Right): MM's made from metal crosses on circuit board. Such structures are amenable to being incorporated into textiles [6].

In addition, THz imaging is an active research area for personnel detection and security; e,g,, it is important to know the effects of textiles in THz imaging, as well as eventually for THz-imaging countermeasures.

MM's are composite materials exhibiting a negative refractive index within a frequency range. This leads to refraction through negative angles via Snell's law. It follows that a flat slab of MM acts as a focusing element. MM's have been realized in the microwaves by fabricating metal capacitive-inductive structures, e.g. wires, split-ring resonators, crosses, etc., on circuit boards or other substrates (Fig. 2). Because the process is cumbersome for bulk MM's, it has only been applied in the microwaves, but not at shorter wavelengths.

THz properties of textiles *are entirely unexplored*. Textiles provide high potential to enable chemical sensors exploiting the effects of PC and MM's. This is because textiles can be engineered to possess structure on the right length scale for THz PC's, i.e., 10 μm to 1 mm. Textiles can be composed of polymers or silica fibers, which have significant indices of refraction; moreover, metal can be incorporated to produce textile MM's in the THz regime.

Electromagnetic textiles have been studied extensively by us (Denison), providing effective-media and percolation-physics models of these textiles. In the '80s, we developed effective-media models for the resistive properties of camouflage fabrics for the U.S. Army. In the '90s these were combined with method of moments modeling, and this work has progressed into scalable effective media models describing percolation physics of complex structures.

Other NTC-funded research: In M02-CL06 Photonic Crystal-Based Polymer Optical Fibers the applications are in the near-infrared or visible, and the fiber itself has PC structure. Although it involves PC's, M02-C L06 is in fact irrelevant to the proposed work.

Approach:
The proposed research brings together the production of wovens and knits incorporating engineered materials with the electromagnetic properties of the resulting textiles in the THz range. Off-the-shelf and custom textiles will be characterized by THz radiation to understand the diffractive properties as well as to identify important chemical (spectroscopic) effects between ~500 GHz and 10 THz. The use of textiles for chemical sensing applications using THz radiation will be explored. Feasibility of PC and MM's applications of textiles in the THz regime will be studied, and optimized textiles will be produced. The central aim of the program is to extend our knowledge base by providing basic knowledge of the THz properties of textiles with an emphasis on PC and MM effects.

THz Properties of Textiles: A key aim of the proposed program of research is the THz characterization of textiles. In this part of the proposed work, the THz radiation scattered by textiles will be studied. THz radiation will be generated photoconductively; a 100 fs (femtosecond) pulsed Ti:Sapphire laser is incident on an electrically biased photoconductor (semi-insulating or low-temperature GaAs) biased by a dc electric field (Citrin and Ralph) [7]. The suddenly created photocurrent produces electromagnetic pulses in the THz range [8,9]. These THz pulses are coupled out of the photoconductor and into freespace with a hyperhemispherical silicon lens or with a broadband fragmented aperture antenna (Denison). The pulses are incident on the textile, and the scattered THz radiation as a function of scattering angle is detected using electro-optic sampling. This yields both amplitude and phase information of the scattering process (both the real and the imaginary part of the spatially dependent dielectric function of the textile). When the THz wavelength is close to the periodicity of the textile, one expects strong scattering—similar to a grating effect. Propagation near grazing angle or scattering by layered or three-dimensionally structured textiles will be related to PC effects, i.e., strong dispersion (large real part of the dielectric constant) is expected when the wavelength is close to the periodicity of the yarns in the textile in the direction of propagation. In addition to these effects, chemical (i.e., spectroscopic) effects associated with the constituents of the textile as well as the effects of ad/absorbed materials will be studied. THz imaging is an emerging technique for medical applications; the specific role of textiles that are used in bandages and dressings will be studied. Electromagnetic modeling of experiments based on the finite-difference time-domain (FDTD) method will be carried out (Citrin).

THz PC Effects in Textiles: Having established the basic THz properties of textiles, engineered textiles (Realff) will be fabricated to enhance PC effects. These textiles will be produced with the appropriate yarns per cm (wovens or knits) and employing materials with high dielectric constant (polymers, silica fiber). In addition, different knits and wovens will be studied; for example a flat weave is likely to produce effects associated with square-lattice PC's while a six-fold symmetric basket weave may exhibit effects close to a hexagonal lattice. The aim is to obtain significant modification to the real part of the dielectric constant in restricted frequency ranges (not necessarily a photonic bandgap), associated with an electric-field enhancement between the yarns.

Textile Chem/Bio THz Sensors: If electric-field enhancements are obtained, we will study the effect on the propagation of THz signals through appropriately designed textiles with ad/absorbed agents. These will include polar and nonpolar liquids sprayed onto textiles, as well as commercially obtained DNA. The aim is to demonstrate detection of agents at levels well below their detectivity in freespace or deposited on flat metal or dielectric surfaces.

Textile THz MM's: Textiles incorporating appropriately designed metal-wrapped yarns or other structures will be produced (Realff) as guided by electromagnetic simulations (Citrin). Three-dimensional weaves or knits will be studied with an eye to bulk isotropic THz MM's. These will be experimentally characterized insofar as their THz properties. One signature of MM's to be studied is the focusing of THz waves by a flat structure.

Textile THz Systems: Layering textiles optimized for PC and MM properties may enable textile THz systems. Focusing and field-enhancement will be explored as a means to increase detectivity of chem./bio agents ad/absorbed in textiles. Feasibility of incorporating such textiles into clothing willl be investigated.

This Year's Goal:
THz scattering experiments will be carried out on off-the-shelf textiles to identify key issues and to separate out chemical effects intrinsic to textiles. Textiles appropriate for PC effects will be identified or engineered. Textiles with electric-field enhancements will be designed. The effects of ad/absorbates will be studied. Electromagnetic simulations will be carried out in conjunction with experiment. In addition, simulation work on textile MM's will be initiated. Subsequent years will be devoted to the remaining tasks.

Outreach to Industry:
The military is expected to be the primary initial customer with the civilian market to follow. NTC-funded work will leverage team-member contacts with DOD funding agencies. Industrial partners will be sought.

New Resources Required:
These include materials and supplies including textiles, chemicals, photoconductors, repair and maintenance of laser system. Two pc's will be purchased that will be dedicated to the electromagnetic simulations. Funds will be used to support two graduate students, one undergraduate student, and partial summer salary for team members. Funds for essential travel to disseminate results will be requested.