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Metamaterials on parylene thin film substrates: Design, fabrication, and characterization at terahertz frequency

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We design, fabricate, and characterize terahertz (THz) resonant metamaterials on parylene free-standing thin film substrates. Several different metamaterials are investigated and our results show strong electromagnetic responses at THz frequencies ranging from 500 GHz to 2.5 THz. The complex frequency dependent dielectric properties of parylene are determined from inversion of reflection and transmission data, thus indicating that parylene is an ideal low loss substrate or coating material. The biostable and biocompatible properties of parylene coupled with the multifunctional exotic properties of metamaterials indicate great potential for medical purposes such as THz imaging for skin cancer detection. © 2010 American Institute of Physics.

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Parylene, discovered in the middle of past century, is the generic name of a family of polymers that has 20 variants, yet only three of them are most commonly used, Parylene N, C, and D.¹ Due to its excellent mechanical, physical, electrical, and barrier properties, parylene is widely used in many areas, such as nanotechnology, electronics, medical, and pharmacopoeia industries.^{2,3} Industry applications typically use a chemical vapor deposition technique in order to form a parylene layer, with thicknesses ranging from hundreds of angstroms to several millimeters.⁴ The advantage of this process is that the coating forms from a gaseous monomer without an intermediate liquid stage. Unlike liquid coatings, this technique ensures the parylene completely penetrates all crevices and uniformly coats surfaces such as sharp points, cavities, edges, corners, and micro/nanoscale pores. The thin film is conformal for almost every exposed surface and is pinhole-free.⁵ Parylene-C is deposited at room temperature and is compatible with micro-electro-mechanical systems (MEMS) technology processes. And it can also be readily separated from the substrates after the completion of device fabrication. Parylene films are chemically and biologically inert, very stable, and nearly unaffected by most acids, alkalines, or organic solvents. Another striking property of parylene films is that it is biocompatible and biostable which enable its wide use in medical areas such as implantable devices.⁶ Other applications which benefit from parylene's excellent properties include the following: circuit boards,⁷ ultrasonic applications,⁸ and surgical devices.⁹ Parylene has excellent dielectric properties as follows: low dielectric constant, low loss, and high dielectric strength, even in the form of very thin films.¹⁰ These excellent properties stem from the fact that the film is conformal and free of defects, and suggest the use of parylene as a substrate material for electro-

magnetic metamaterials operating within the terahertz (THz) range.

Electromagnetic metamaterials, artificial materials made from structured composites, have attracted much attention from the scientific community after experimental demonstration of negative index of refraction in 2000.¹¹ Other striking examples and blooming areas of metamaterial research includes super lenses¹² and invisible cloaks.¹³ It is predicted that numerous applications will thrive within the THz frequency range. Metamaterials operating in the THz range have had great successes in filling in the so-called "electromagnetic gap," lying between microwave and infrared frequencies. Some metamaterials devices have been demonstrated such as modulators, filters, and perfect absorbers.¹⁴ Perfect absorbers have been reported as an imaging tool at THz frequencies and may have application in biomedical diagnostic areas such as skin cancer detection.¹⁵ The use of parylene as a substrate or coating for metamaterials is further motivated by the fact that many diagnostic detectors are implanted directly into the human body. Materials which constitute the detector should be stable and compatible with human body—one of the salient features of parylene films. In this letter, we demonstrate that metamaterials fabricated on parylene thin film substrates have strong resonances at THz frequencies with low loss. This verifies the potential usage of parylene as metamaterial coatings or substrates for bioimplanting applications within the human body.

We designed and fabricated several types of metamaterials, as show in Fig. 1. Some of these, such as the canonical split ring resonator (SRR) and the electrical ring resonator, are well characterized at THz frequencies, shown in Figs. 1(a) and 1(e), respectively. A silicon wafer was used as a platform for fabrication. After dehydration baking the wafers at 150 °C, ten micron thick film of parylene-C was deposited using a Labcoater 2 Parylene Deposition Unit (Specialty Coating Systems, Indianapolis, IN). The dimer charge was

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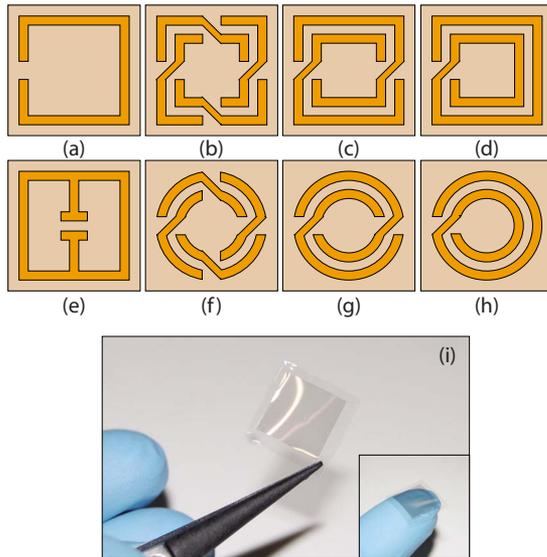


FIG. 1. (Color online) [(a)–(h)] Schematic of the various metamaterials fabricated and characterized on parylene thin film substrates. The size of each unit cell is $100 \times 100 \mu\text{m}^2$. The outer dimension of each metamaterial is $72 \times 72 \mu\text{m}^2$ and the line width is $8 \mu\text{m}$. All the gaps are $8 \mu\text{m}$ wide. For the spiral structures, the gap between inner and outer metal is $4 \mu\text{m}$. (i) Photographs of metamaterials on parylene thin film substrate.

vaporized at 175°C and 1 Torr, decomposed to its monomer (paraxylylene) at 690°C and 0.5 Torr, and deposited on the wafers at 25°C and 0.1 Torr. The metamaterials were next created utilizing a photoresist (AZ nLOF 2020) using conventional photolithography. Then, a 10 nm/200 nm thick Ti/Au layer was sputter deposited onto the parylene-C. Next, we performed lift-off by placing the wafer in an acetone bath. Finally, the parylene-C substrate containing metamaterial structures were peeled off the silicon wafer, shown in Fig. 1(i).

We simulated the electromagnetic response of the metamaterials using the commercial FDTD program Microwave Studio. Dimensions were modeled as according to Fig. 1. Perfect electric and perfect magnetic boundary conditions are used to polarize the electric and magnetic field components, vertically and horizontally with respect to Fig. 1. Ports were used on the remaining two boundaries to simulate a plane wave incident on the metamaterial. The transient solver is used to obtain the complex S-parameters.

The metamaterial/parylene samples were characterized using a Fourier-transform infrared (FTIR) spectrometer. A liquid-helium-cooled Si bolometer is used as a detector and a Hg arc lamp as the source. A polarizer is used to obtain the desired electric field orientation. We use both a $50 \mu\text{m}$ thick mylar and germanium coated $6 \mu\text{m}$ thick mylar beam splitter to cover the desired frequency range. The samples were mounted at normal incidence for transmission measurements and 30° incidence from normal for the reflection measurements.

We also characterized the complex dielectric properties $[\tilde{\epsilon}(\omega) = \epsilon_1 + i\epsilon_2]$ of parylene thin films using the FTIR. Both the transmission $T(\omega)$ and reflection $R(\omega)$ were measured for a $20 \mu\text{m}$ thick parylene free standing film. We make an approximation in this system; treating the parylene permeability equal to the free space value. $T(\omega)$ and $R(\omega)$ were then inverted using the Levenberg–Marquardt algorithm to numerically solve for the frequency dependent complex dielec-

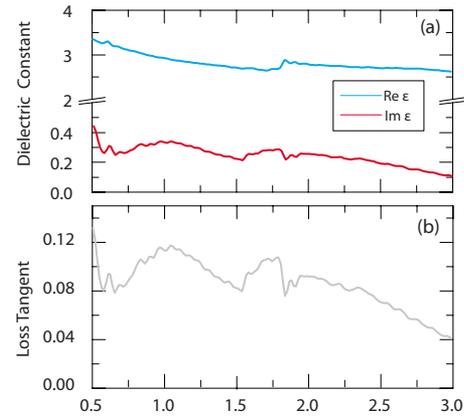


FIG. 2. (Color online) (a) Dielectric constant and (b) Loss tangent of $20 \mu\text{m}$ thickness parylene thin film.

tric function for the parylene thin film.¹⁶ In the program code we assume normal incidence reflection which does not significantly affect the results. We extracted both the real (ϵ_1) and imaginary part (ϵ_2) of the dielectric constant and calculated the loss tangent of the parylene film, as shown in Figs. 2(a) and 2(b), respectively. The result clearly shows that parylene thin films are a low loss material within the THz frequency range, and thus make a good substrate material for potential applications.

The transmission for all metamaterials is displayed in Fig. 3. Insets are optical microscope images of the fabricated metamaterials. The red curve indicates vertical electrical polarization and blue horizontal polarization, with respect to Fig. 1. Figure 3(a) is the transmission spectrum for the canonical SRR. The SRR transmission shows strong resonances at about 0.5, 1.5, and 2.3 THz. It is worth highlighting that the resonance strength is much higher than reported for SRRs on GaAs substrates; all the three resonances achieve values below 10%. Similar resonance strength also

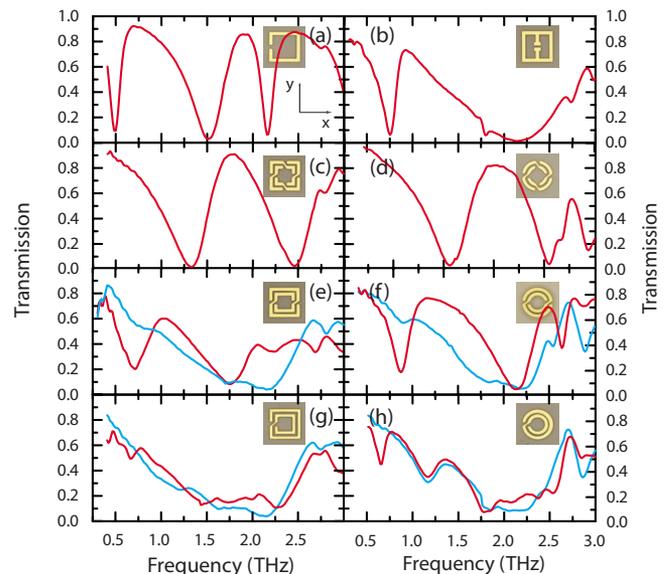


FIG. 3. (Color online) Transmission spectrum for metamaterials on parylene thin film. The red curves represent electric field polarized along y direction and the blue ones are for x polarization. Insets are the optical microscopic images or corresponding metamaterials.

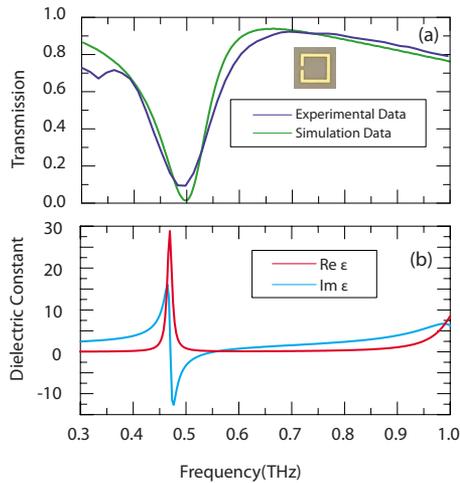


FIG. 4. (Color online) (a) Comparison of simulation and experimental result of the SRR. The green curve is simulated and the blue one is experimental (b) Fitted dielectric constant from experimental result of SRR.

appears in Figs. 3(c) and 3(d); they both have strong resonances and are relatively broad-band. A comparison of the experimental and simulated transmission of the low frequency resonance of the SRR is shown in Fig. 4(a), and good agreement is evident. We also fitted the dielectric constant of SRR on parylene substrate shown in Fig. 4(b).

In conclusion, we designed, fabricated, and characterized several different metamaterials on parylene thin film substrates. Due to the low loss properties of parylene films, metamaterials exhibit strong electromagnetic response at

THz frequencies. Coupled with the biostable and biocompatible properties of parylene film, our results indicate the potential future use of metamaterial/parylene composites for medical purposes, or other various applications.

- ¹J. S. Song, S. Lee, S. H. Jung, G. C. Cha, and M. S. Mun, *J. Appl. Polym. Sci.* **112**, 3677 (2009).
- ²P. Hanefeld, U. Westedt, R. Wombacher, T. Kissel, A. Schaper, J. H. Wendorff, and A. Greiner, *Biomacromolecules* **7**, 2086 (2006).
- ³E. M. Schmidt, J. S. McIntosh, and M. J. Bak, *Med. Biol. Eng. Comput.* **26**, 96 (1988).
- ⁴A. A. Tracton, *Coatings Technology Handbook* (CRC, 2008).
- ⁵D. C. Rodger, J. D. Weiland, M. S. Hamayun, and Y. C. Tai, *Sens. Actuators B*, **117**, 107 (2006).
- ⁶G. E. Loeb, M. J. Bak, M. Salcman, and E. M. Schmidt, *IEEE Trans. Biomed. Eng.* **BME-24**, 121 (1977).
- ⁷F. A. Lindberg, *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, **14**, 790 (1991).
- ⁸S. Aoyagi, K. Furukawa, D. Ono, K. Ymashita, T. Tanaka, K. Inoue, and M. Okuyama, *Sens. Actuators, A*, **94**, 145 (2008).
- ⁹C. P. Tan, B. R. Seo, D. J. Brooks, E. M. Chandler, H. G. Craighead, and C. Fischbach, *Integr. Comp. Biol.*, **1**, 587 (2009)
- ¹⁰D. Devanathan and R. Carr, *IEEE Trans. Biomed. Eng.* **BME-27**, 671 (1980).
- ¹¹D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, *Phys. Rev. Lett.* **84**, 4184 (2000).
- ¹²J. B. Pendry, *Phys. Rev. Lett.* **85**, 3966 (2000).
- ¹³D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, *Science* **314**, 977 (2006).
- ¹⁴N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, *Phys. Rev. Lett.* **100**, 207402 (2008).
- ¹⁵N. I. Landy, C. M. Bingham, T. Tyler, N. Jokerst, D. R. Smith, and W. J. Padilla, *Phys. Rev. B* **79**, 125104 (2009).
- ¹⁶M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference, and Diffraction of Light* (Cambridge University Press, Cambridge, 1999).