Gangbuster frequency selective surface metamaterials in terahertz band

D.J. Shelton, J.W. Cleary, J.C. Ginn, S.L. Wadsworth, R.E. Peale, D.K. Kotter and G.D. Boreman

Frequency selective surfaces using Ag dipole antenna elements have been simulated, fabricated and tested to demonstrate improved narrowband transmission compared to the current state of the art in the 1–2 THz. Several designs are presented including variations in dipole packing density, and sensitivity to a cladding layer. The sharpest resonant response was measured to have a bandwidth of 90 GHz at a centre frequency of 1.3 THz, for a Q of 14.5, which is the highest thus far reported for a terahertz narrowband filter. In addition, the sensitivity of the resonance of the structures to material properties may be exploited as a way to measure the permittivity and loss tangent of thin films in the terahertz band.

Introduction: Metamaterials may be used for narrowband transmission filters and other photonic applications. The subclass of metamaterials described in this Letter consisted of periodic arrays of planar antenna elements called a frequency selective surface (FSS) [1]. The sub-wavelength sized FSS elements were encased in a mechanically flexible cladding. Narrowband transmission filters are characterised by a Q factor defined as the ratio of the centre frequency to the full width at half maximum (FWHM) of the filter. The current state of the art for metamaterial narrowband filters in the 1–2 THz band has been achieved using a periodic array of Cu cross-slot elements on a glass substrate, and a Q factor of 6.1 at a centre frequency of 1.54 THz [2]. Recent work has demonstrated the use of split-ring resonator metamaterials in the terahertz band which have a Q factor of 4.2 at a centre frequency of 1.05 THz [3]. In this Letter a new class of terahertz FSS is explored based on an adaptation of gangbuster elements [4], which consist of dipole antennas having lengths approximately equal to half of the wavelength at peak transmission. The dipoles are staggered as shown in Fig. 1 so that the periodicity is small on both the x- and y-axis to prevent diffraction effects. Following the nomenclature of RF gangbuster surfaces, the terahertz gangbuster designs are classified by a packing 'type' defined by the ratio of the major to minor axis as shown in Fig. 1. In this Letter type 2, 3, and 4 gangbuster surfaces are evaluated in the 1–2 THz band. In addition, the sensitivity of the filter's resonance location and width to the permittivity and loss tangent of the cladding layer was also investigated and shown to have applications in the determination of unknown permittivities for materials of potential utility in the terahertz band.

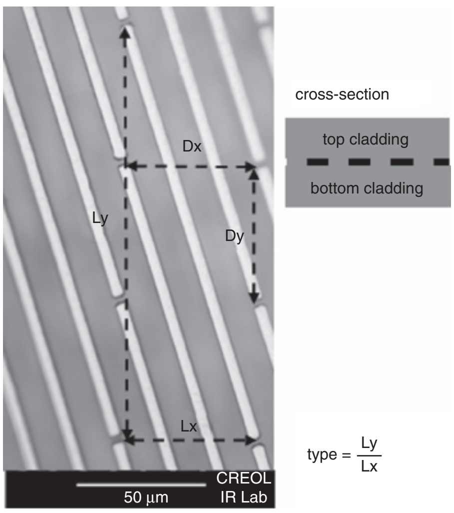

Fig. 1 *Dipole metamaterial array configuration indicating gangbuster type with cross-section shown on right where thicknesses of top and bottom cladding layers are typically 9 µm and metal elements in centre are approximately 200 nm*

Prediction method: The response of the terahertz gangbuster FSS was simulated using the Ohio State Periodic Method of Moments (PMM) code. A sheet resistance based on four-point probe measurements and the Drude model was used in the PMM simulations. The metallic elements were immersed in the centre of an 18 µm-thick cladding layer. The permittivity of the cladding layer at 1.5 THz was initially unknown.

Test device fabrication: Identifying suitable metamaterial substrates in the terahertz band is challenging compared to the RF or IR bands. RF substrates are very thin compared to the wavelength of convenient mechanical thickness, while substrates in the IR band are typically many wavelengths thick, resulting in Faby-Perot resonances that are very closely spaced. To avoid substrate loss and to minimise the impact of unwanted substrate modes, we used a membrane substrate consisting of an 18 µm layer of the flexible polymer HD Microsystems liquid polyimide. The IR properties of liquid polyimide have been previously measured and the material was found to have low absorption at long wavelengths [5]. Detailed device fabrication and processing using liquid polyimide has been described in [6].

Results: The spectral transmission of the metamaterials was measured using a Bomem Fourier transform terahertz spectrometer with an Hg arc lamp source and an He-cooled Si bolometer. The beam diameter of the measurement region was 10 mm. For the gangbuster to function properly, the incident radiation must be linearly polarised and oriented parallel to the dipoles. Thus a wire grid polariser was placed between the source and the elements. The required orientation of the polariser may be determined by taking the arc tangent of the number corresponding to the gangbuster type.

Measured and simulated results for linearly polarised input are shown in Fig. 2 for three different element packing types. Although the most densely packed surface, type 4, would be expected to result in the highest Q factor, measurements show that the effect of finite conductivity was to reduce the Q factor and hence widen the spectral response. As the packing density increased, so did metallic loss, and the type 4 surface had smaller throughput and a lower Q factor than the type 2 metamaterials. The type 2 surface was measured to have the highest Q factor (14.5) reported to date in the terahertz band. Table 1 lists the dimensions and Q factors for the metamaterials. Agreement between simulation and measurement was excellent for the type 2 and 3 packing densities, but the simulation predicted a larger Q factor for the type 4 packing density than was measured. The PMM software uses a sheet resistance approximation to represent a metal surface, which limited the simulation's accuracy when finite conductivities were used. Thus, the simulation predicted a narrower bandwidth than was measured, which was most noticeable for the type 4 surface. Measured transmission was below 25% for all of the devices owing to substrate reflection loss and 50% of the incident radiation being blocked by the linear polariser.

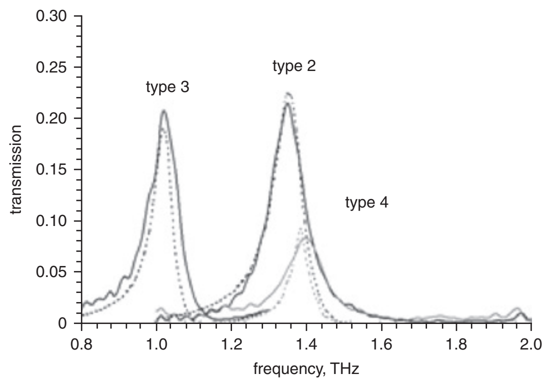

Fig. 2 *Transmission for gangbuster type 2, 3, 4 with linearly polarised input*
Measured data, solid lines; model predictions, broken lines

Table 1: Gangbuster dimensions and measured results

	Lx (µm)	Ly (µm)	Dx (µm)	Element width (µm)	Centre frequency (THz)	Q factor
Type 2	35.5	142	81	25	1.35	14.5
Type 3	22.0	198	71	6	1.03	10.0
Type 4	8.67	139	37	5	1.41	11.6

Comparing the modelled and measured filter resonance in terms of centre frequency, peak transmission strength, and width, we were able

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to obtain a fit for the permittivity and loss tangent of the cladding layer, which are presented in Table 2. The centre frequency had the strongest dependence on permittivity, while the peak transmission depended most strongly on the loss tangent. If a set of gangbuster surfaces of various types or element lengths (with a resulting range of resonant frequencies) were fabricated on a given thin film substrate, this dependence could be used to determine the terahertz optical properties of the film material. We used the sensitivity of the metamaterial resonance to the properties of the metallic elements and the surrounding dielectric to measure the terahertz permittivity and loss tangent of the popular spin-on dielectric BCB (benzocyclobutene, or Dow cyclotene), which can be used in the construction of terahertz metamaterials. In this portion of the study, BCB was spun on top of the type 2 elements in place of the top cladding layer of liquid polyimide. The permittivity and loss tangent of BCB at 1.41 THz were thus fitted, with results being shown in Fig. 3 and Table 2.

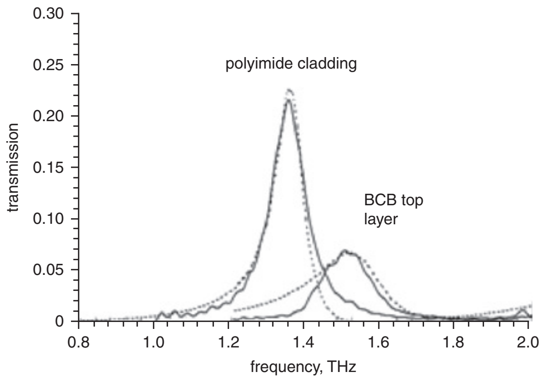

Fig. 3 *Top cladding for type 2 gangbuster replaced with BCB and compared to all polyimide cladding*

Measured data, solid lines; model predictions, broken lines

Table 2: Material properties (sheet resistance measured, permittivities fitted)

Element thickness	Element metal	Sheet resistance	Cladding thickness
200 nm	Ag	0.385 Ω/Sq	18 μm
Dielectric	**Frequency**	**Permittivity**	**Loss tangent**
Polyimide	1.03 THz	3.6	0.0042
Polyimide	1.35 THz	3.55	0.011
BCB	1.41 THz	1.85	0.24

Conclusion: FSS metamaterials consisting of gangbuster elements immersed in a flexible cladding layer were demonstrated to have the highest resonant Q factor yet observed (14.5) for a filter in the 1–2 THz band. In addition, the FSS resonance was shown to be sensitive to material properties of the metals and dielectrics; this property was used to measure the unknown properties of useful materials at THz frequencies.

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D.J. Shelton, J.W. Cleary, J.C. Ginn, S.L. Wadsworth, R.E. Peale and G.D. Boreman (*University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816, USA*)

E-mail: dshelton@creol.ucf.edu

D.K. Kotter (*Idaho National Labs, Idaho Falls, ID 83415, USA*)

References

1 Monacelli, B., Pryor, J., Munk, B.A., Kotter, D., and Boreman, G.D.: 'Infrared frequency selective surface based on circuit-analog square loop design', *IEEE Trans. Antennas Propag.*, 2005, **53**, (2), pp. 745–752
2 Porterfield, D.W., Hesler, J.L., Densing, R., Mueller, E.R., Crowe, T.W., and Weikle, R.M. II: 'Resonant metal-mesh bandpass filters for the far infrared', *Appl. Opt.*, 1994, **33**, (25), pp. 6046–6052
3 Chen, H.T., O'Hara, J.F., Azad, A.K., Taylor, A.J., Averitt, R.D., Shrekenhamer, D.B., and Padilla, W.J.: 'Experimental demonstration of frequency-agile terahertz metamaterials', *Nature Photonics*, 2008, **2**, pp. 295–298
4 Munk, B.A.: 'Frequency selective surfaces' (John Wiley & Sons, New York, 2000)
5 Folks, W., Ginn, J., Shelton, D., Tharp, J., and Boreman, G.: 'Spectroscopic ellipsometry of materials for infrared micro-device fabrication', *Phys. Status Solidi*, 2008, **5**, (5), pp. 1113–1116
6 Shelton, D., Tharp, J., Zummo, G., Folks, W., and Boreman, G.: 'Fabrication of periodic microstructures on flexible polyimide membranes', *J. Vac. Sci. Technol., B*, 2007, **25**, (6), pp. 1827–1831

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