Terahertz Dielectric Sensor Based on Novel Hexagon Meta-Atom Cluster

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Abstract ─ In this paper, we report meta-atom sensor based on planar hexagon split ring resonators. The sub-wavelength structure is designed to operate in terahertz frequency band. A modified version of split ring resonator geometry is simulated for sensing dielectric changes by placing thin dielectric layers as sample materials on the full frontal surface of sensor. The effective parameters are retrieved using Nicolson-Ross and Weir method. The meta-atom sensor shows significant changes in resonant frequency as a function of transmission (magnitude of S_{21} parameter) response, which was observed when the sensor is loaded with the dry layer of dielectric materials of different dielectric constants. This paper contributes new shape of meta-atom structure used as a terahertz dielectric sensor. The proposed sensor can be used in multitudinous terahertz near field sensing applications.

Index Terms ─ Dielectric sensor, meta-atom, near field, split ring resonator, terahertz.

I. INTRODUCTION

Meta-atoms or metamaterials are attractive man-made materials that can influence the light waves in astonishing manners. The structure of metamaterial is primarily constructed of subwavelength metallic resonators printed all together on dielectric substrate materials. Their electromagnetic properties are mainly consequent from the resonating metal structure rather than from atoms and or molecules as they do in conventional materials [1].

Meta-atoms can be manufactured to get a wide range of electromagnetic characteristics at desired frequencies. Such characteristics are still not founded in naturally occurring materials, which is why they named ‘meta’, which means beyond the materials. The natural materials typically occupy the positive real electric permittivity and magnetic permeability; whereas, negative values of the permittivity and permeability are possibly attainable in nature through the radiation manipulation [2]. Meta-atoms, e.g., thin metallic wires [3], can reduce and shift the fundamental frequency to a lower part of the frequency spectrum, thus resulting in a negative permittivity and permeability at lower frequencies. In nature, achieving negative values of permeability is uncommon but can be obtained from magnetic resonances in ferro-magnets at high frequencies. Meta-atoms, such as split-ring resonators (SRR) [4] and cut-wire pairs [5], can exhibit magnetic dipoles and negative permeability in response to magnetic waves up to the optical regime [6]. Achieving negative values of electromagnetic responses in meta-atoms open ways to realize double-negative characteristics, in which the permittivity and permeability are less than zero at the same frequencies resulting in negative-index material. Such types of sophisticated materials have never been occurred in the nature [7].

In their initial stages, the meta-atoms were tested in combination with the transmission wires to exhibit effective parameters of negative permittivity and permeability [8]. Negative index materials have incited a very wide interest in meta-atoms due to their strange behavior, and became the hub of metamaterial research and extend its operation in visible frequency spectrum [9].

Meta-atoms offered volume of opportunities in order to improve functional abilities of existing microwave and optical components and devices with exploring unexampled applications. Current research explored so far super lenses [10], biosensors based on meta-atoms, which are sensitive to small changes in the amount and response of a sample [11] and invisibility cloaks for the camouflage of an object from being detected [12]. Terahertz metamaterial research is newly emerged technology; that is why fundamental studies,

Submitted On: August 31, 2014
Accepted On: May 20, 2015

novel designs and advanced metamaterial applications are yet to be sufficiently explored. It is conceived that this novel research field will have great impact on science and engineering.

The split ring resonators have been used as fundamental circuits in numerous meta-atom applications. Because of their fascinating properties, they are still at the top of all their counterparts. They proved their effectiveness in high frequency applications where the other circuits do not. The artificial structures exhibit negative resonances at negative refractive index regions, which is impossible for any natural material. Meta-atom resonators find useful applications in detection of gas leakage and defects [13] infrared and thermal emission detectors [14] and in imaging [15,16].

Split ring resonators of different geometries are used as a basic unit cell for sensor clusters because of their unique characteristics of having negative permeability, permittivity and refractive index, which is numerically proved in open literature. Initially, meta-atoms were proposed for microwave frequency band and later they were introduced in terahertz and infrared frequency. In recent years, meta-atoms have proved their worth in terahertz nondestructive sensing applications because of the non-ionizing characteristics. There are many analytical models of split ring resonators are reported up to now.

Split ring resonator based meta-atom sensor is a circuit that can provide specific quantitative analytical information. Split ring resonators are arranged in circular and rectangular geometries for various scientific applications. The effect of substrate material cannot be ignored at very high frequencies; also metal strips offer very high loss [17]. The loss can be minimized by utilizing very thin and low permittivity substrate material [18]. Considering high loss situation, low permittivity substrate is utilized in this report.

There are a number of geometrical shapes reported in the literature demonstrating the usage of SSR. S-shape resonators [19], omega resonators [20], various shapes of hexagons [21,22,23,24,25] and v-shape resonators [26] and other geometries are reported for left-handed meta-atoms applications. Meta-atoms with double negative index have attracted the interest of the scientists, especially in the terahertz regime [27].

Meta-atoms exhibit concentrated electromagnetic field, which is necessary to get the improved selectivity of sensors for detection of quite minute amount of analytes [28]. Such detection ability opens minds for new applications to be explored through the use of meta-atoms. For example, meta-atoms have replaced the use of metallic conductors in many applications where surface plasmons were employed [29]. The sub wavelength sized meta-atoms are capable to be used as sensing devices at high frequencies [30]. Resonant modes of two dimensional sub wavelength resonators are suitable for sensing applications [31]. The non-destructive property of meta-atoms makes them highly suitable candidate for label free sensing of biochemical substances. Meta-atoms are also proposed for sensing of dielectrics by using electric permittivity near-zero narrow waveguide channels [32]. A meta-atom based microwave nondestructive evaluation sensor to detect materials with smaller imperfections compared to a wavelength was reported in [33]. It is revealed through studies that the sensitivity and resolution of ordinary sensors can be significantly enhanced by incorporation of meta-atoms.

Split ring resonators with different shapes are used for the sensors and microelectronic devices. Split ring resonator based biosensor with a small electrical size to detect the occurrence of bio molecular binding was experimentally demonstrated [34]. The structure of that biosensor was consisted of two pairs of SRR and a planar microwave transmission line.

So far, meta-atom based thin dielectric layer sensing structures have proved their effectiveness in the field of sensing. These electrically small devices are potential candidates for future scientific applications.

II. MATERIAL AND METHODS

The meta-atoms are periodically arranged in the form of cluster, which is illustrated in Fig. 1. Meta-atoms are of particular interest in the terahertz regime because of high spectral resolution, where most natural materials exhibit only weak electric and magnetic responses, and hence, cannot be utilized for sensing of minute samples. The introduction of terahertz meta-atom is believed to be an important step that can further advance terahertz research and development. Simulation results demonstrate the responses and their effective parameters like the real parts of negative permeability and electric permittivity.

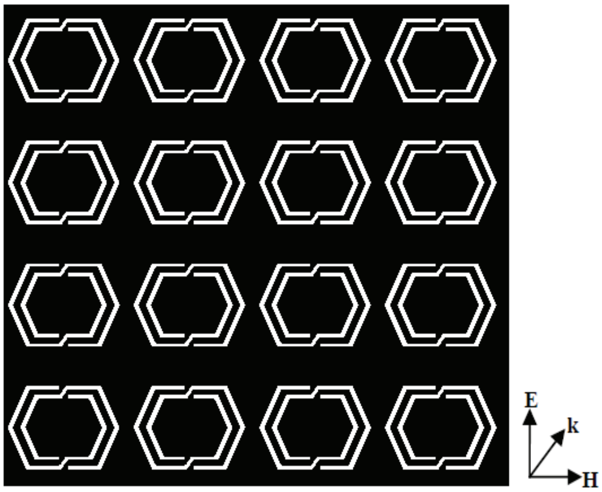

Fig. 1. 4 by 4 novel meta-atom cluster.

The increase in the number of split rings will increase the number of split gaps and metallization on the substrate; thus, an increase in the surface electric field will be observed on the split gap areas and overall surface of the metamaterial unit cell. The increasing values of overall capacitance, which includes gap and surface capacitance, will reduce the operating frequency as they are inversely proportional to each other. A simple inductor and capacitor (*LC*) tank circuit can represent the analogy of split ring resonator. The split rings form the magnetic inductance and can be considered as inductors. The capacitance is mainly formed in and around split gap areas.

The split ring resonator exhibit electromagnetic resonance when the electric energy stored in capacitor; i.e., gap is in balance with the magnetic energy stored in the inductors, i.e., split rings. The changes in capacitance, *C* and inductance, *L* due to dielectric loading from bio-molecule leads to a considerable shift in the frequency of resonance [35] as shown in equation (1):

$$f_C = \frac{1}{2\pi\sqrt{LC}}. \qquad (1)$$

The unit cell of the dielectric sensor is designed with new shape of hexagonal split ring resonators (HSRR). Two HSRR are aligned face to face with modified gaps at the top and bottom spaced with 1.5 μm to each other on a thin dielectric substrate. Figure 2 shows the geometric dimensions of the HSRR. The proposed meta-atom cluster is simulated using Computer Simulation Technology (CST) studio suite 2014 to compute the complex scattering constitutive parameters. The simulated scattering parameters are obtained for the retrieval of effective parameters.

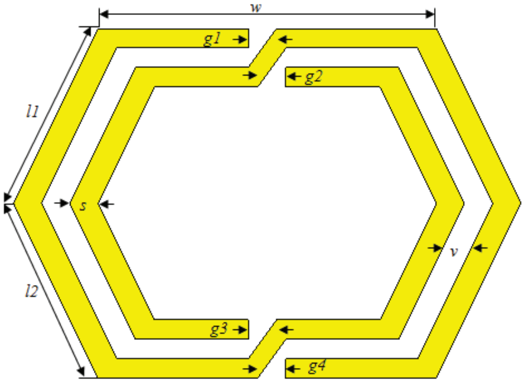

Fig. 2. Meta-atom unit cell design structure.

The effective parameters of hexagon split ring resonators are extracted using Nicolson-Ross and Weir method [36,37]. The Kramers-Kronig relationship [38] is further applied in order to get improved results. The unit cell dimensions are 30μm×30μm×0.5μm=450μm^3. The width of inner and outer gap area is made 1.5 μm. The split ring is made of gold strips with the permittivity ε_r=11.9.

The gold strips are printed on the substrate. Selection of the material strip is based on the fact that electrical conductivity of gold and annealed copper is 5.8×10^7 Siemens per meter. The strip thickness is 0.017 μm. The use of low permittivity materials causes deeper resonances at terahertz frequency [39]. Due to this reason, RT5880LZ with relative permittivity (ε_r) of 1.96 and permeability (μ_r) of 1 is used as a substrate material to achieve smaller unit to wavelength ratio. The cell dimensions are summarized in Table 1.

Table 1: Meta-atom unit cell dimensions

Parameters	Dimensions (μm)
Gap (*g1*, *g2*, *g3*, *g4*)	1.5
Strip width (*s*)	1
Strip spacing (*v*)	1
Strip length (*l1*, *l2*)	10.062
Horizontal width (*w*)	20
Substrate thickness	0.5

The effective parameters like permittivity and permeability are calculated using equations (2) and (3) as:

$$\mu_r = \frac{2}{jk_0 d} \times \frac{1-\upsilon_2}{1+\upsilon_2}, \qquad (2)$$

$$\varepsilon_r = \frac{2}{jk_0 d} \times \frac{1-\upsilon_1}{1+\upsilon_1}. \qquad (3)$$

In above equations, 'k_0' is the wave number and '*d*' is the substrate thickness.

The scattering parameters are represented as the sum and difference terms as given in equations (4) and (5):

$$\upsilon_1 = S_{21} + S_{11}, \qquad (4)$$

$$\upsilon_2 = S_{21} - S_{11}. \qquad (5)$$

A. Quality factor of the resonant meta-atom cluster

Quality factor or Q factor is an important figure of merit that needs to be considered when describing the sensitivity of the meta-atom cluster based dielectric sensors. The Q factor of a resonance peak or dip can be calculated from the resonant frequency (f_0) and the frequency bandwidth (Δf) of the resonant peak at -3 dB power point [40], as shown in equation (6). Quality factors in the microwave portion of terahertz frequency operated meta-atoms are observed approximately 10 [41]. Unloaded Q factor of reported meta-atom cluster is calculated using -3 dB bandwidth formula and the result is summarized in Table 2.

$$Q = f_0 / \Delta f. \qquad (6)$$

Table 2: Unloaded Q factor at resonant frequency

Resonant Frequency	Quality Factor
3.9 THz	95

The value of Q factor is proportional to the location of resonant frequency. This value is also dependent on the sharpness of the transmission. The deeper and narrower transmission dip with near to zero reflection results in higher value of Q factor.

III. RESULTS AND DISCUSSION

The sensor is constituted by hexagon split ring resonators, which are periodically arranged on a thin dielectric substrate material. Perpendicular incidence external field is applied in order to get strong electric and magnetic field response from meta-atom sensor. The direction of incidence is such that it is perpendicular to the metamaterial surface plane to observe the transmission spectra of the metamaterial unit cell. The electric and magnetic field is polarized in parallel to the long edges of the sensor along y-axis and z-axis respectively. The perpendicular incident waves can induce electric response when the electric field polarization is parallel to the long edges of the structure, and the parallel incident waves are easy to infuse the magnetic response when there is a loop in the metamaterial split ring resonator structure. The strong *LC* resonance can also be observed by the surface electric field distribution, and that the electric field is mainly focused on the upper and lower capacitive gap area as shown in Fig. 3.

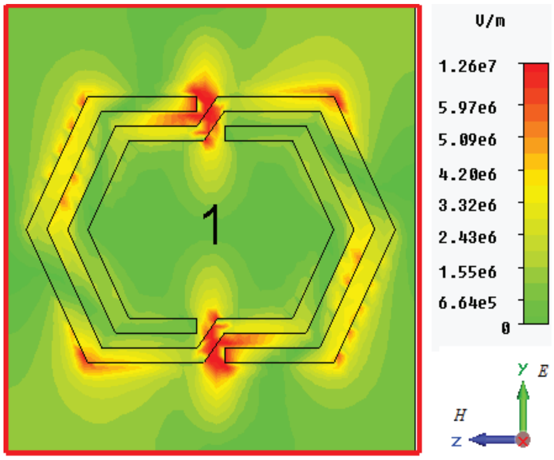

Fig. 3. Surface electric field distribution localized in the split gaps of hexagonal meta-atom unit cell.

The localization of surface electric field distribution is concentrated on the small gap areas because of increased capacitance. The overall surface electric field of sensor is not attributed only to the field at the split gaps.

The effective complex permeability of proposed meta-atom sensor at resonant frequency is shown in Fig. 4. According to that, the real value of complex permeability is negative at the frequency at the resonant frequency. There is only one instance where the real part of effective permittivity goes negative, and that is the region of resonance. The effective permittivity graph is shown in Fig. 5. The real part of electric permittivity and magnetic permeability exhibit a sharp negative value around the fundamental resonant frequency and remains negative in the frequency region from 3.9 to 4.1 THz.

Split ring resonators are asymmetric structures and mainly used in microwave and terahertz applications because of the presence of loop structure in their structural geometry. At the electric resonant frequency, the current flows parallel to the polarization direction, which indicates that the meta-atom split ring resonator acts like an electric dipole. The flowing surface current in the long metallic wires generates magnetic response, which is why, the retrieved permeability goes negative around the resonant frequency. In comparison to the magnetic response, the electric response is stronger, which can be observed in negative value of electric and magnetic response of the retrieved permittivity and permeability.

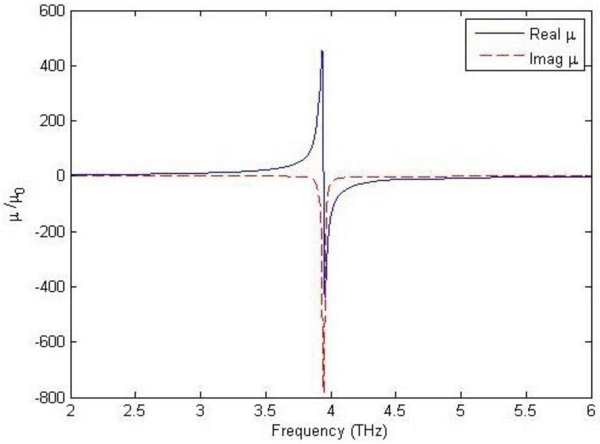

Fig. 4. Effective permeability.

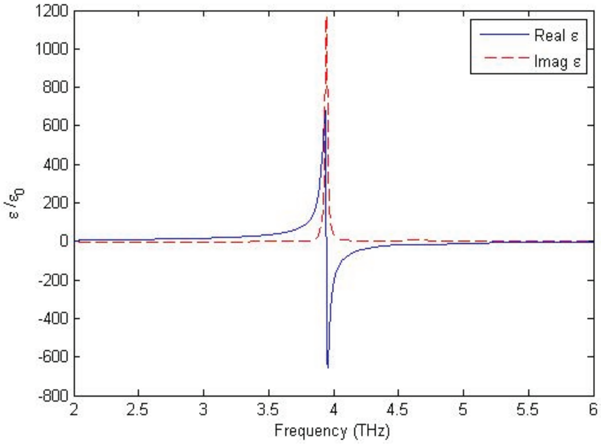

Fig. 5. Effective permittivity.

The reason of this response is the perpendicular incidence and parallel polarization of electric field component. When flowing current on the two corners of split ring resonator goes in phase causes less induction in the metallic wires and magnetic field becomes weaker at resonant frequency.

A stop band is observed at the resonant frequency under unloading condition or when the sample layer is not loaded on the surface of sensor. At the same instant, the real part of the effective permittivity goes sharp to the negative value. The real part of the retrieved permeability also becomes negative around the resonant frequency. Simultaneous negative values of permittivity and permeability can cause refractive index to exhibit negative value. The imaginary value of effective complex permittivity is appeared to be positive, which somehow satisfies the conditions for passivity and causality keeping in view of limitations related to Nicholson-Ross and Weir method [42], in which the meta-atom cluster behaves as a power source with no power dissipation. The dielectric constant and thickness of substrate is kept constant in all experimental simulations along with the sample thickness, which is maintained to 100 nanometer. Scaling down the sensor size to the suitable values will result in sensing the presence of thinner sample layers. There is a shift in the transmission observed when the meta-atom cluster based sensor was loaded with three different dielectric materials of different dielectric constants, as shown in Fig. 6.

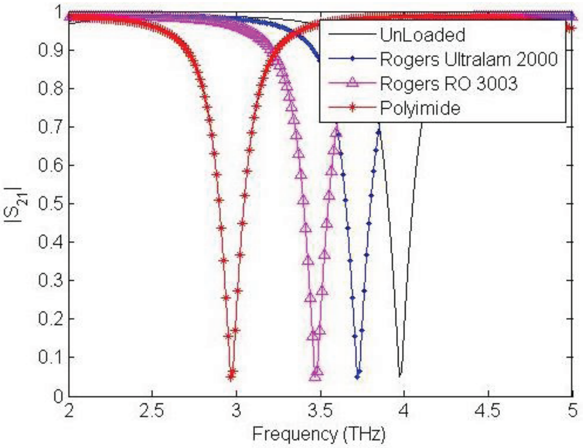

Fig. 6. Transmission spectra of meta-atom cluster under unloading and loading conditions.

Changing electric field causes the change in refractive index that yields the shift in transmission on frequency domain when the structure is loaded with dielectric materials of different permittivity. These materials were simulated for different loading conditions and are tabulated in Table 3.

Table 3: Dielectric materials used for sample loadings

Material	Relative Permittivity	Relative Permeability	Shift Δ*f*/*f*
Rogers Ultralam 2000	2.5	1	0.2 THz
Rogers RO 3003	3	1	0.5 THz
Polyimide	3.5	1	1.1 THz

Unloaded transmission (S_{21} magnitude) is observed at the resonant frequency when the surface of the sensor was not exposed to the sample material. Transmission shift was observed when the cluster was loaded consecutively with Rogers Ultralam 2000, Rogers RO 3003 and Polyimide.

IV. CONCLUSION

The planar hexagon meta-atom cluster based dielectric sensor reported in this paper exhibits left handed characteristics at THz frequency band. The presence of the thin dry dielectric layers on the surface of the sensor was observed as the transmission (S_{21} parameter magnitude) is shifted towards lower frequency values. Significant changes were observed under loading samples with higher dielectric constants. Fabrication and dielectric characterization of such meta-atom cluster based sensor is the future extension of this research work.

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