

METAMATERIAL SPLIT RING RESONATOR, METAMATERIAL SPLIT RING RESONATOR ARRAY AND ENERGY HARVESTING APPARATUS

Cross-reference to Related Applications

[0001] The present application claims the benefit of the Singapore provisional patent application No. 10201606290S filed on 29 July 2016, the entire contents of which are incorporated herein by reference for all purposes.

Technical Field

[0002] Embodiments relate generally to a metamaterial split ring resonator, a metamaterial split ring resonator array, and an energy harvesting apparatus.

Background

[0003] When EM (electromagnetic)/RF (radio frequency) waves are shielded, the shielding material absorbs the incoming wave and converts them to heat. Although this amount of heat is very low, it will be significant as the power and frequency increases. One example is the infrared spectrum which has EM wavelength between 700 nm to 1 mm, which corresponds to a frequency between 430 THz to 300 GHz.

[0004] From the daily experience, the incoming infrared waves will heat up materials. In the context of buildings, the heating of the façade increases cooling load, and causes discomfort for the occupants. A method of removing heat from the façade is to convert the incoming heat (infrared) into electrical energy, and transfer this energy away. This is an example of an extension of the EM/RF shielding and energy harvesting concept, whereby incoming EM/RF energy is converted to electrical energy and transported to another location.

[0005] It has been known that the amount of energy that can be harvested from ambient RF is limited. Among the many available sources such as mechanical vibration, thermal, light (solar or artificial) and ambient RF, ambient RF remains the lowest power density available for harvesting. Despite this, it should be noted that ambient RF is

typically available all the time. For low power electronics, this means that power is available at all times.

[0006] The conventional method of harvesting energy is using various forms of antenna. From the study, it is found that a single antenna has limited energy harvesting capabilities. As the gain of an antenna is proportional to its area, the amount of energy that an antenna can harvest is limited by this fact. However, a single antenna has its upper limit in terms of size. The best size for a single antenna is between a quarter wavelength to one wavelength. Thus, it is not feasible to increase the size of the antenna beyond one wavelength to harvest more EM/RF energy.

[0007] The next logical step in EM/RF energy harvesting would then be to use many smaller antennas to form into an array. An array can increase in size indefinitely. The combined effects in an antenna array increase the gain, and thus the amount of RF energy that can be converted to DC (direct current). Traditionally, the individual smaller antenna elements are integrated with impedance transformers which take up much space. Accordingly, the area utilization of conventional antenna arrays is not high, and thus not very efficient in RF energy harvesting. In fact, conventional antenna arrays are not meant for the purpose of energy harvesting, but are initially designed for beam forming, null steering, and beam steering. To adapt to EM/RF energy harvesting, a different approach has been recently made popular, in part due to the improvements in RF electronics. Instead of RF combining techniques, each element in the RF energy harvesting array is instead loaded with a diode. With this implementation, DC combining techniques can be used. The advantage of this is that space wasting impedance transformers can be removed, and the elements can be spaced closer together, thus increasing the area utilization. The previously detrimental element mutual coupling effects can now be designed favorably to increase the performance of the antenna array. As the elements are spaced closer, the size of each element also reduces.

[0008] As the size of the elements reduces, the implementation of DC combining antenna array approaches the concept of metamaterials (MM). Metamaterials are materials that are not found in nature. Although metamaterials are not naturally occurring, they can be made by usual materials such as copper. Instead of elements, each metastructure making up the metamaterials is a cell that resonates at a particular frequency. The simplest cell structure is that of a split ring resonator (SRR). The split at

the top of the ring act as a capacitor, while the arms of the ring act as inductor, forming a conventional LC circuit. When the SRRs resonates, energy is stored.

[0009] It is desired to improve an antenna and an antenna array to further increase the amount of harvested energy.

Summary

[0010] Various embodiments provide a metamaterial split ring resonator. The metamaterial split ring resonator may include a first split ring including a first split at a first edge of the first split ring and a second split at a second edge of the first split ring. The first edge is opposite to the second edge. The metamaterial split ring resonator may further include a second split ring inside the first split ring and concentric with the first split ring, wherein the second split ring includes a third split at a first edge of the second split ring adjacent to the first edge of the first split ring. The first split ring includes a first pair of stubs extending inwardly from the first split, and the second split ring includes a second pair of stubs extending inwardly from the third split.

[0011] Various embodiments further provide a metamaterial split ring resonator array. The metamaterial split ring resonator array includes a plurality of metamaterial split ring resonators arranged adjacent to each other in an array. Each metamaterial split ring resonator includes a first split ring including a first split at a first edge of the first split ring and a second split at a second edge of the first split ring, wherein the first edge is opposite to the second edge. Each metamaterial split ring resonator further includes a second split ring inside the first split ring and concentric with the first split ring, wherein the second split ring includes a third split at a first edge of the second split ring adjacent to the first edge of the first split ring. The first split ring includes a first pair of stubs extending inwardly from the first split, and the second split ring includes a second pair of stubs extending inwardly from the third split.

[0012] Various embodiments further provide an energy harvesting apparatus. The energy harvesting apparatus includes a plurality of metamaterial split ring resonators arranged adjacent to each other in an array. Each metamaterial split ring resonator includes a first split ring including a first split at a first edge of the first split ring and a second split at a second edge of the first split ring, wherein the first edge is opposite to

the second edge. Each metamaterial split ring resonator further includes a second split ring inside the first split ring and concentric with the first split ring, wherein the second split ring includes a third split at a first edge of the second split ring adjacent to the first edge of the first split ring. The first split ring includes a first pair of stubs extending inwardly from the first split, and the second split ring includes a second pair of stubs extending inwardly from the third split. The energy harvesting apparatus further includes a plurality of rectifiers, wherein each rectifier is coupled to the respective metamaterial split ring resonator and is configured to convert energy harvested by the metamaterial split ring resonator to a respective direct current. The energy harvesting apparatus further includes a direct current combining circuit coupled to the plurality of rectifiers, and configured to combine the direct currents produced by the plurality of rectifiers.

Brief Description of the Drawings

[0013] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments are described with reference to the following drawings, in which:

Fig. 1 shows a metamaterial split ring resonator according to various embodiments.

Fig. 2 shows a metamaterial split ring resonator array according to various embodiments.

Fig. 3 shows a schematic diagram of an energy harvesting apparatus according to various embodiments.

Fig. 4(a) shows a single split ring resonator. Fig. 4(b) shows a S11 (return loss/reflection coefficient) plot of the single split ring resonator of Fig. 4(a).

Fig. 5(a) shows a front view of a metamaterial split ring resonator according to various embodiments. Fig. 5(b) shows a back view of the metamaterial split ring resonator of Fig. 5(a) according to various embodiments.

Fig. 6 shows a diagram comparing simulated S11 results of metaresonators in different shapes.

Fig. 7 shows a diagram illustrating the optimization results of S11 response when stub lengths of the hexagonal metaresonator of various embodiments are varied.

Fig. 8(a) shows a CST® model of a metaresonator according to various embodiments, and Fig. 8(b) shows a photograph of a fabricated metaresonator according to various embodiments.

Fig. 9 shows a photograph depicting the back of the fabricated metaresonator with a RF coaxial cable soldered according to various embodiments.

Fig. 10 shows a diagram illustrating a comparison between the simulated and measured results according to various embodiments.

Fig. 11 shows radiation gain patterns of both simulated and measured antennas of Fig. 8 according to various embodiments.

Fig. 12(a) shows a CST® model of a metamaterial split ring resonator array according to various embodiments. Fig. 12(b) shows a top view of a fabricated metamaterial split ring resonator array according to various embodiments. Fig. 12(c) shows a bottom view of the fabricated metamaterial split ring resonator array of Fig. 12(b) according to various embodiments.

Fig. 13 shows a S11 comparison between the simulated metaresonator array of Fig. 12(a) and the fabricated metaresonator array of Fig. 12(b) according to various embodiments.

Fig. 14 shows gain comparison between a unit element and an array according to various embodiments.

Fig. 15(a) shows a front view of an arrangement of a metaresonator array according to various embodiments. Fig. 15(b) shows a back view of the metaresonator array of Fig. 15(a).

Fig. 16 shows S11 results of the metaresonator array of Fig. 15(a) according to various embodiments.

Fig. 17 shows an experimental set up using an off the shelf router according to various embodiments.

Fig. 18 shows an experimental set up according to various embodiments using a signal generator connected to an amplifier and a monopole antenna.

Detailed Description

[0014] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized, and structural and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0015] Various embodiments provide a metamaterial (MM) split ring resonator (SRR), a metamaterial split ring resonator array, and an energy harvesting apparatus.

[0016] Embodiments described below in context of the metamaterial split ring resonator are analogously valid for the metamaterial split ring resonator array and the energy harvesting apparatus, and vice versa. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment.

[0017] It will be understood that any property described herein for a specific metamaterial split ring resonator may also hold for any metamaterial split ring resonator described herein. It will be understood that any property described herein for a specific metamaterial split ring resonator array may also hold for any metamaterial split ring resonator array described herein. It will be understood that any property described herein for a specific energy harvesting apparatus may also hold for any energy harvesting apparatus described herein. Furthermore, it will be understood that for any metamaterial split ring resonator or metamaterial split ring resonator array or energy harvesting apparatus described herein, not necessarily all the components described must be enclosed in the metamaterial split ring resonator or metamaterial split ring resonator array or energy harvesting apparatus, but only some (but not all) components or steps may be enclosed.

[0018] In the specification the term “coupled” (or “connected”) herein may be understood as electrically coupled, or as mechanically coupled, for example attached or

fixed, or just in contact without any fixation, and it will be understood that both direct coupling or indirect coupling (in other words: coupling without direct contact) may be provided.

[0019] In order that various embodiments may be readily understood and put into practical effect, particular embodiments will now be described by way of examples and not limitations, and with reference to the figures.

[0020] According to various embodiments, the concepts of electrically small antenna (ESA), antenna array, and metamaterial (MM) are combined to form a metamaterial resonator (also referred to as a metaresonator, an ESA, or an antenna in this description) and an array of metaresonators to harvest EM/RF (electromagnetic or radio frequency) energy. According to the description below, if a maximum cell size of one tenth of a wavelength is chosen, the three concepts can be combined to achieve a EM/RF shielding and energy harvesting metaresonator array.

[0021] Various embodiments provide a design of an ESA unit cell (also referred to as a metaresonator unit cell, or an antenna unit cell) that can resonate at high frequencies (3 MHz to 30MHz), very high frequencies (30 MHz to 300MHz), ultra high frequencies (300MHz to 3GHz), or super high frequencies (3GHz to 30GHz); where the incoming wavelength is significantly larger than the antenna. The ESA unit cell that will be used in the EM/RF shielding and energy harvesting array may need to satisfy three main conditions. The first condition is that the size of each unit cell is 0.1λ in order to combine the concept of ESA, antenna array, and MM.

[0022] Next, as the metaresonator and the metaresonator array can be applied in a building, the surface areas available will be large. As such, to use this EM/RF shielding and energy harvesting array, the costs have to be kept low. To do so, regular PCB (printed circuit board) technologies have to apply with the low cost FR-4 material as the substrate. In PCB technologies, there are four classes of printed boards under the Association Connecting Electronics Industries (IPC) standards. Class 1 is for general electronic products, Class 2 is for dedicated service electronic products, Class 3 is for high reliability electronic products, and Class 3/A is for space and military avionics. As those descriptions suggest, Class 1 is the cheapest but with the lowest standard, while Class 3/A is the most expensive but has the highest standard. In most cases, Class 2 has a good balance between cost and standard.

[0023] Lastly, this unit cell/element needs to be able to tessellate over a surface. In addition, for a given 0.1λ size, the area needs to be as big as possible to have the highest possible gain. According to various embodiments, a regular polygon shaped unit cell may be used as it has good reflection and rotational symmetry, which is important as the designed unit cell/element is to emulate an atom as much as possible.

[0024] According to various embodiments, a unit cell that may be used in the EM/RF shielding and energy harvesting array is provided, which is a metamaterial split ring resonator (also referred to as a metaresonator, an ESA, or an antenna) as described with reference to Fig. 1 below. The design of the metamaterial split ring resonator includes a single split ring resonator (SRR) with a complementary split ring resonator (CSRR), which can resonate at lower frequencies due to the CSRR. This is a method of loading an ESA given the constraints of a PCB antenna. The feed points at the bottom of the metaresonator serve as the ports where a load such as diode or resistor can be inserted. In an array including a plurality of this unit cell, the feed points serve as a connection to interlink each unit cell.

[0025] Fig. 1 shows a metamaterial split ring resonator 100 according to various embodiments.

[0026] The metamaterial split ring resonator 100 may include a first split ring 110 including a first split 112 at a first edge 102 of the first split ring 110 and a second split 114 at a second edge 104 of the first split ring 110. The first edge 102 is opposite to the second edge 104. The metamaterial split ring resonator 100 may further include a second split ring 120 inside the first split ring 110 and concentric with the first split ring 110, wherein the second split ring 120 includes a third split 122 at a first edge 132 of the second split ring 120 adjacent to the first edge 102 of the first split ring 110. The first split ring 110 includes a first pair of stubs 116 extending inwardly from the first split 112, and the second split ring 120 includes a second pair of stubs 126 extending inwardly from the third split 122.

[0027] The first split ring 110 may be referred to as a single split ring resonator (SRR), and the second split ring 120 may be referred to as a complementary split ring resonator (CSRR).

[0028] In other words, various embodiments provide the metamaterial split ring resonator 100 which includes an outer split ring 110 and an inner split ring 120

concentric with each other, wherein the outer split ring 110 includes the first split 112 and the inner split ring 120 includes the third split 122 at the same side of the metamaterial split ring resonator 100. The outer split ring 110 further includes the second split 114 at another side of the metamaterial split ring resonator 100 opposite to the side of the metamaterial split ring resonator 100 where the first split 112 is located. The outer split ring 110 includes the first pair of stubs 116 extending into the interior of the outer split ring 110 from two ends of the first split 112. The inner split ring 120 includes the second pair of stubs 126 extending into the interior of the inner split ring 120 from two ends of the third split 122.

[0029] In this context, a split ring refers to a loop or a ring having a split (i.e., a gap or an opening) at the perimeter of the loop/ring, in other words, the split ring is not a closed loop or a closed ring. The split ring may be in any suitable shapes, such as circle, oval, or polygon. According to various embodiments, the first split ring 110 and the second split ring 120 are in the same shape. In an exemplary embodiment, the first split ring 110 and the second split ring 120 may be in a polygonal shape.

[0030] According to various embodiments, the first split ring 110 and the second split ring 120 are hexagonal rings. In various embodiments, the first split ring 110 and the second split ring 120 are regular hexagonal rings.

[0031] According to various embodiments, the first split ring 110 and the second split ring 120 are arranged in the same orientation. In this description, the same orientation may include an identical orientation, and a similar orientation with slight variation of less than 5° from an identical orientation. When the first split ring 110 and the second split ring 120 are arranged in the same orientation, the respective edges of the first split ring 110 may be at least substantially parallel to the respective adjacent edges of the second split ring 120. In an illustrative example, the first edge 102 of the first split ring 110 is at least substantially parallel to the first edge 132 of the second split ring 120 which is adjacent to the first edge 102.

[0032] In this specification, the term “at least substantially parallel” shall be understood to include a perfect parallel arrangement, as well as a substantially parallel arrangement which may have a slight departure (e.g. less than 5°, e.g., 1°, e.g., 0.5°) from the perfect parallel arrangement. The term “at least substantially perpendicular” shall be understood to include a perfect perpendicular arrangement, as well as a substantially

perpendicular arrangement which may have a slight departure (e.g. less than 5° , e.g., 1° , e.g., 0.5°) from the perfect perpendicular arrangement.

[0033] According to various embodiments, the first pair of stubs 116 and the second pair of stubs 126 are at least substantially parallel to each other, and are at least substantially perpendicular to the first edge 102 of the first split ring 110 and the first edge 132 of the second split ring 120. The first pair of stubs 116 and the second pair of stubs 126 may extend or protrude inwardly toward a center line of the metamaterial split ring resonator 100, wherein the center line is at least substantially parallel to the first edge 102 of the first split ring 110 and the first edge 132 of the second split ring 120. In this specification, the stub may refer to an edge or leg extending or protruding from the end of the first split 112 or the third split 122, and may form an ending portion of the first split ring 110 or the second split ring 120 as shown in the embodiments of Fig. 1.

[0034] According to various embodiments, lengths of the first pair of stubs 116 and the second pair of stubs 126 are determined based on a desired resonant frequency of the metamaterial split ring resonator 100.

[0035] According to various embodiments, lengths of the first pair of stubs 116 and the second pair of stubs 126 are adjustable to fine tune a resonant frequency of the metamaterial split ring resonator 100.

[0036] According to various embodiments, the first pair of stubs 116 and the second pair of stubs 126 have lengths in a range between 0.5mm to 1.1mm.

[0037] According to various embodiments, the metamaterial split ring resonator 100 is an electrically small antenna (ESA).

[0038] According to various embodiments, the metamaterial split ring resonator 100 has a maximum dimension substantially equal to or less than 0.1λ , wherein λ represents a wavelength of a resonant frequency of the metamaterial split ring resonator 100. In an exemplary embodiment, the maximum dimension of the metamaterial split ring resonator 100 may deviate from 0.1λ by up to 10%. In other embodiments, the maximum dimension of the metamaterial split ring resonator 100 may be less than 0.1λ to 0.0795λ .

[0039] According to various embodiments, the second split 114 forms feed points configured to connect with a diode. The two ends of the second split 114 may serve as the feed points. The metamaterial split ring resonator 100 connected with the diode is

configured to convert RF energy to DC with the diode serving as a rectifier, and may be referred to as a rectenna. In other embodiments, the second split 114 may form feed points configured to connect with other types of rectifier or load, such as a semiconductor switch or a resistor.

[0040] Fig. 2 shows a metamaterial split ring resonator array 200 according to various embodiments.

[0041] The metamaterial split ring resonator array 200 may include a plurality of metamaterial split ring resonators 100, e.g. the metamaterial split ring resonator 100 described in various embodiments of Fig. 1 above, arranged adjacent to each other in an array. Various embodiments of the metamaterial split ring resonator 100 are analogously valid for the metamaterial split ring resonator array 200, and vice versa. Similar to the embodiments described in Fig. 1, each metamaterial split ring resonator 100 may include a first split ring 110 including a first split 112 at a first edge 102 of the first split ring 110 and a second split 114 at a second edge 104 of the first split ring 110. The first edge 102 is opposite to the second edge 104. Each metamaterial split ring resonator 100 may further include a second split ring 120 inside the first split ring 110 and concentric with the first split ring 110, wherein the second split ring 120 includes a third split 122 at a first edge 132 of the second split ring 120 adjacent to the first edge 102 of the first split ring 110. The first split ring 110 includes a first pair of stubs 116 extending inwardly from the first split 112, and the second split ring 120 includes a second pair of stubs 126 extending inwardly from the third split 122.

[0042] Although Fig. 2 shows an embodiment wherein the metamaterial split ring resonator array 200 includes six resonators surrounding one resonator located in the center, it is understood that the metamaterial split ring resonator array 200 may include any suitable number of resonators 100 arranged in any suitable form of array in various embodiments. In exemplary embodiments, the plurality of metamaterial split ring resonators 100 may be arranged in a one-dimensional array, or in a two-dimensional array (e.g. in rows and columns).

[0043] According to various embodiments, the plurality of metamaterial split ring resonators 100 may be tessellated. This may refer to the embodiments that the plurality of metamaterial split ring resonators 100 are tessellated without any spacing or gap between adjacent resonators 100.

[0044] According to various embodiments, the plurality of metamaterial split ring resonators 100 may be arranged with a spacing between adjacent metamaterial split ring resonators 100. In various embodiments, the spacing between adjacent metamaterial split ring resonators 100 may be uniform along the adjacent edges of the adjacent metamaterial split ring resonators 100. In various embodiments, the spacing between adjacent metamaterial split ring resonators 100 may be substantially the same throughout the array 200.

[0045] According to various embodiments, the plurality of metamaterial split ring resonators 100 are arranged in the same orientation, which may refer to the orientation wherein the stubs of the plurality of metamaterial split ring resonators 100 extend along and protrude towards substantially the same direction. As an illustrative example in Fig. 2, the plurality of metamaterial split ring resonators 100 are arranged in the orientation that the second splits of the metamaterial split ring resonators 100 are at the bottom side, and the stubs are arranged at the top side of the metamaterial split ring resonators 100 and are extending vertically and protruding downwardly. In other embodiments, the plurality of metamaterial split ring resonators 100 may be arranged in other suitable orientations, wherein the stubs of the plurality of metamaterial split ring resonators 100 may extend along and protrude towards substantially the same direction.

[0046] According to various embodiments, the plurality of metamaterial split ring resonators 100 may be arranged in different orientations, for example, the stubs of different metamaterial split ring resonators may extend along or protruding towards different directions, e.g. as shown in the embodiments of Fig. 15 below.

[0047] According to various embodiments, the plurality of metamaterial split ring resonators 100 are arranged on a first surface of a substrate, wherein the plurality of metamaterial split ring resonators 100 are connected to direct current (DC) lines on a second surface of the substrate via the respective second splits. The second surface is opposite to the first surface. In various embodiments, the substrate may be a printed circuit board (PCB).

[0048] According to various embodiments, the first split ring 110 and the second split ring 120 of each metamaterial split ring resonators 100 are in the same shape. In an exemplary embodiment, the first split ring 110 and the second split ring 120 of each metamaterial split ring resonators 100 may be in a polygonal shape.

[0049] According to various embodiments, the first split ring 110 and the second split ring 120 of each metamaterial split ring resonator 100 are hexagonal rings. In various embodiments, the first split ring 110 and the second split ring 120 of each metamaterial split ring resonator 100 are regular hexagonal rings.

[0050] According to various embodiments, the first split ring 110 and the second split ring 120 of each metamaterial split ring resonator 100 are arranged in the same orientation. In each metamaterial split ring resonator 100, the respective edges of the first split ring 110 may be at least substantially parallel to the respective adjacent edges of the second split ring 120. In an illustrative example, the first edge 102 of the first split ring 110 is at least substantially parallel to the first edge 132 of the second split ring 120 adjacent to the first edge 102.

[0051] According to various embodiments, the first pair of stubs 116 and the second pair of stubs 126 in each metamaterial split ring resonator 100 are at least substantially parallel to each other, and are at least substantially perpendicular to the first edge 102 of the first split ring 110 and the first edge 132 of the second split ring 120. The first pair of stubs 116 and the second pair of stubs 126 in each metamaterial split ring resonator 100 may extend or protrude inwardly toward a center line of the metamaterial split ring resonator 100, wherein the center line is at least substantially parallel to the first edge 102 of the first split ring 110 and the first edge 132 of the second split ring 120.

[0052] According to various embodiments, lengths of the first pair of stubs 116 and the second pair of stubs 126 in each metamaterial split ring resonator 100 are determined based on a desired resonant frequency of the respective metamaterial split ring resonator 100.

[0053] According to various embodiments, lengths of the first pair of stubs 116 and the second pair of stubs 126 in each metamaterial split ring resonator 100 are adjustable to fine tune a resonant frequency of the respective metamaterial split ring resonator 100.

[0054] According to various embodiments, the first pair of stubs 116 and the second pair of stubs 126 in each metamaterial split ring resonator 100 have lengths in a range between 0.5mm to 1.1mm.

[0055] According to various embodiments, each metamaterial split ring resonator 100 is an electrically small antenna (ESA). If each metamaterial split ring resonator 100 is

electrically small and able to function individually as an electrically small antenna, they can be combined into an array without using impedance transformers.

[0056] According to various embodiments, each metamaterial split ring resonator 100 has a maximum dimension substantially equal to or less than 0.1λ , wherein λ represents a wavelength of a resonant frequency of the metamaterial split ring resonator 100. In an exemplary embodiment, the maximum dimension of each metamaterial split ring resonator 100 may deviate from 0.1λ by up to 10%. In other embodiments, the maximum dimension of the metamaterial split ring resonator 100 may be less than 0.1λ to 0.0795λ .

[0057] According to various embodiments, the second split 114 of each metamaterial split ring resonator 100 forms feed points configured to connect with a respective diode. The two ends of the second split 114 may serve as the feed points. The metamaterial split ring resonator 100 connected with the diode is configured to convert RF energy to DC with the diode serving as a rectifier, and may be referred to as a rectenna. When the plurality of metamaterial split ring resonator 100 is packed in the antenna array 200, each with its own rectifier, the need for impedance transformer may be eliminated. In other embodiments, the second split 114 of each metamaterial split ring resonator 100 may form feed points configured to connect with other types of rectifier or load, such as a respective semiconductor switch or a respective resistor.

[0058] When a plurality of unit cells is arranged in an array, the resonant frequency will be shifted, which may often be uncontrollable and the resulting array design will not operate at the desired frequency. According to various embodiments above, due to the four stubs design of the unit element/cell 100, the length of the stubs can be adjusted to fine tune the resonant frequency to the desired value after the metamaterial split ring resonator 100 are combined into an array. Alternatively or additionally, the spacing, i.e. the distance of separation, between each unit cell 100 may also be used alternative to or in conjunction with the adjustment of stub lengths for fine tuning the resonant frequency to the desired value. Due to this combination, low frequency resonance at the desired value is possible.

[0059] Fig. 3 shows a schematic diagram of an energy harvesting apparatus 300 according to various embodiments. The energy harvesting apparatus 300 may include a plurality of metamaterial split ring resonators 100 (e.g. the metamaterial split ring resonator 100 described in the embodiments of Fig. 1 above) arranged adjacent to each

other in an array (e.g. the metamaterial split ring resonator array 200 described in the embodiments of Fig. 2 above). Various embodiments of the metamaterial split ring resonator 100 and the metamaterial split ring resonator array 200 are analogously valid for the energy harvesting apparatus 300, and vice versa.

[0060] Similar to the embodiments described in Fig. 1, each metamaterial split ring resonator 100 may include a first split ring including a first split at a first edge of the first split ring and a second split at a second edge of the first split ring. The first edge is opposite to the second edge. Each metamaterial split ring resonator may further include a second split ring inside the first split ring and concentric with the first split ring, wherein the second split ring includes a third split at a first edge of the second split ring adjacent to the first edge of the first split ring. The first split ring includes a first pair of stubs extending inwardly from the first split, and the second split ring includes a second pair of stubs extending inwardly from the third split.

[0061] The energy harvesting apparatus 300 further includes a plurality of rectifiers 320, wherein each rectifier 320 is coupled to the respective metamaterial split ring resonator 100 and is configured to convert energy harvested by the metamaterial split ring resonator 100 to a respective direct current. The energy harvesting apparatus 300 further includes a direct current combining circuit 330 coupled to the plurality of rectifiers 320, and configured to combine the direct currents produced by the plurality of rectifiers 320. The output 340 of the direct current combining circuit 330 may be a combined direct current.

[0062] According to various embodiments, the energy harvesting apparatus 300 may further include a load coupled to the direct current combining circuit 330, e.g. to receive the output 340 of the direct current combining circuit 330.

[0063] According to various embodiments, each rectifier 320 includes a diode connected with or across the second split of the respective metamaterial split ring resonator 100, such that EM or RF energy received by the metamaterial split ring resonators 100 is converted to direct currents. The metamaterial split ring resonators 100 connected with the respective diodes may form the respective rectennas. In various embodiments, the rectifier 320 may further include a resistor. According to various embodiments, any other suitable type of rectifier 320, e.g. semiconductor switch, may be connected with or across the second split of the respective metamaterial split ring

resonator 100. According to various embodiments, in addition to the rectifier, any suitable type of load, e.g. resistor, may be connected with or across the second split of the respective metamaterial split ring resonator 100.

[0064] According to various embodiments, wherein the energy harvesting apparatus 300 is configured to be applied to a building façade for energy harvesting and shielding of electromagnetic waves. In various embodiments, the energy harvesting apparatus 300 is configured to be applied to other locations, for example, wall partitions, ceilings, or walls of a building, or any other suitable places or surfaces.

[0065] Various embodiments of the metamaterial split ring resonator 100, the metamaterial split ring resonator array 200 and the energy harvesting apparatus 300 are described in more details below.

[0066] The energy harvesting apparatus 300 including the metaresonator array (also referred to as antenna array) according to various embodiments above increases received power.

[0067] The formula for the resulting far-zone E field from an array of identical resonators/antennas is

$$E(\text{total}) = [E(\text{Single element at a single reference point})] \times [\text{array factor}] \quad (1)$$

[0068] From (1), which is also known as the Principle of Pattern Multiplication, it can be seen that if each resonator element of the array is the same, then the array factor, AF, is the main contributor of the resulting far-zone E field. In the case of N-element linear array of uniform amplitude and spacing, the AF is determined as

$$AF = \sum_{n=1}^N e^{j(n-1)(kd \cos \theta + \beta)} \quad (2)$$

[0069] wherein k is the wave vector of $2\pi/\lambda$ for a plane wave,

[0070] d is the element spacing,

[0071] θ is the arrival angle of a wave relative to the array, and

[0072] β is the difference in the phase excitation between the elements.

[0073] Therefore, from equation (2) it is clear that other than individual elements, d and β are the two main factors that affect AF. For the energy harvesting antenna array, it is desirable to have an array that occupies a large area. However, when this is achieved

by increasing the distance between each element, the negative result is the generation of grating lobes. These grating lobes are not desirable in some cases as it reduces the angle of the main lobe, which in turns reduces the gain. In the application of RF energy harvesting, this may not be completely undesirable as the grating lobes can be useful in harvesting RF energy that comes from other angles besides the main lobe.

[0074] In conventional RF energy harvesting antenna arrays, the distance between elements cannot be completely chosen based on the coupling effects or gain of the array considerations. This is due to the inclusion of impedance transformers needed to match the different elements together. It is more so when using corporate feeding method. Impedance transformers take up space between the elements, but they are necessary to combine elements together. However, in some cases, the mutual coupling can be used to some advantage.

[0075] According to the embodiments of Fig. 3, at each antenna/resonator 100 and rectifier 320, RF is individually converted to DC, and the resulting DC is then combined by the DC combining circuit 330. This energy harvesting topology makes it possible to use mutual coupling to some advantages.

[0076] In addition to the possible use of mutual coupling to improve some performance of the antenna array, such as radiation pattern, using DC combiner topology also reduces the need of lengthy impedance transformers and truly makes each antenna/resonator with its own rectifier a rectenna on its own.

[0077] To have a higher area utilization, having individual RF to DC rectifier for each antenna/resonator is needed. This is made possible by the advancing technology in RF components that allows them to be manufactured in smaller packages, with lower energy requirements, and at a decreasing cost.

[0078] From the RF energy harvesting efforts that went from single antenna of different designs, to planar microstrip patch antenna arrays, and then to rectenna arrays, it can be seen that the trend of RF energy harvesting is directed towards having many small rectennas packed as close together as possible to increase the amount of DC power that can be converted.

[0079] As the element size and spacing decreases, the concept of rectenna arrays approaches the concept of metamaterials.

[0080] It is found that for unit cells in a metamaterial to act like atoms in a matter, the size of each unit cell, when used in rectenna design, can be set to be between 0.1λ to 0.2λ .

[0081] With the size of each unit cell between 0.1λ to 0.2λ , and having it applied to antennas, it comes close to the field of electrically small antenna (ESA).

[0082] According to the IEEE standard of definitions, antennas are considered electrically small if the diameter of the sphere containing the antenna is small compared to the wavelength of operating frequency. The definition of electrically small is generally taken as any maximum length smaller than 0.1λ . As such, there is a range of values that an antenna can take to be considered electrically small. In summary, if the antenna maximum dimension is less than 0.1λ to 0.0795λ , it is considered small.

[0083] However, planar antennas with maximum dimension of 0.1λ are difficult to manufacture by standard PCB fabrication process and materials without loading them with passive components. This is due to a limit on how thin each trace can be, and how close the traces be separated. Limitations in PCB technologies are basically a trade-off between cost and tolerances of the fabrication process. The Institute for Printed Circuits (IPC) standard describes four classes of manufacturing, where class 2 allows a trace width as small as about 0.127mm (5 mils), and a trace separation of about 0.0889mm (3.5 mils). In this specification, class 2 is chosen for the good balance between cost and tolerance.

[0084] Since there are issues with the fabrication of 0.1λ ESA using standard PCB fabrication technologies without loading with passive components, the stubbed hexagonal folded dipole ESA loaded with CSRR as shown in Fig. 1 is provided in various embodiments. This ESA has potential to form into an antenna array (e.g., the array of Fig. 2) without using impedance transformers, wherein the antenna array is constructed with optimization of the element separation and the stub lengths, and without affecting the unit element design.

[0085] Constraining the maximum dimension to 0.1λ presents two main advantages: (a) a lumped circuit model analysis can be applied, as the current distribution can be assumed to be uniform in the antenna; and more importantly, (b) the ESA can be combined to form an array without the need to use impedance transformers due to the uniform current distribution.

[0086] To utilize the MM concepts when forming an antenna array out of ESAs, the size of each unit element would need to satisfy the criteria of MM. It has been proved that if the wires making the unit cell are thin compared to the lattice size, and by reducing the classical plasma frequency equation, the maximum size of each cell should be smaller than 0.3989λ . Furthermore, if radius of the wire is not much smaller, then the maximum cell size required can be calculated to be between 0.1λ to 0.2λ , depending on the cell-to-wire dimensions.

[0087] Based on the above, various embodiments provide that the maximum dimension of the unit cell is substantially equal to or less than 0.1λ , which can satisfy the concepts of ESA, combining unit elements into an array without the use of impedance transformers, and MM. By having this size, EM/RF shielding can be realized using MM concepts, while EM/RF energy harvesting can be achieved by using ESA and antenna array.

[0088] When incorporating MM with ESA, an important concept that is taken from MM is the concept of resonance. According to various embodiments, the MM unit cell structure is selected to be a split ring resonator (SRR). This structure is important to MM due to that fact that at the desired operating frequency, the ring and the gap between the ring form a LC resonating circuit. When this concept of SRR is incorporated into ESA, then ESA with a complementary SRR (CSRR) can form as a unit element (e.g. the metaresonator 100 of Fig. 1) in an array (e.g. the metaresonator array 200 of Fig. 2) that can resonate and harvest energy at the desired operating frequency. This type of antenna may be referred to as metaresonator antennas as shown in the embodiments of Fig. 1.

[0089] In conventional planar antenna array designs, impedance transformers are required to interconnect the elements to ensure that their impedances are matched. However, impedance transformers take up space and reduce area utilization. Various embodiments are provided based on the finding that if each element is electrically small and able to function individually as an electrically small antenna (ESA), they can be combined into an array without using impedance transformers. According to various embodiments above, a stubbed hexagonal shaped folded dipole ESA (e.g. the metaresonator 100 of Fig. 1) with a maximum dimension of one tenth of the wavelength is provided. This metamaterial (MM) inspired design of loading the folded dipole with split ring resonator (SRR) overcomes the problem of fabricating ESA of one tenth of the

wavelength using typical PCB fabrication technologies for high frequencies (3 MHz to 30MHz), very high frequencies (30 MHz to 300MHz), ultra high frequencies (300MHz to 3GHz), or super high frequencies (3GHz to 30GHz); e.g. the 2.45 GHz band, the 5.8GHz WiFi band, or mobile communications band.

[0090] In the following, the design of an ESA unit cell, e.g. the metamaterial split ring resonator 100 described above, is described in more detail. Various embodiments may determine a few criteria for the unit cell, including 1) Able to tessellate; 2) Largest area possible for a given maximum dimension; 3) Planar and able to be fabricated using conventional low cost PCB technologies; 4) Able to resonate at frequencies that considers the unit cell electrically small; 5) Have frequency fine tuning capabilities, which is needed when tessellated or arranged into an array.

[0091] In determining the shape of the unit cell, a regular polygon shape may be selected in various embodiments, as it has the best reflection and rotational symmetry. When tessellated, the gaps between each unit cell can also be minimal to maximize area utilization. According to various embodiments, the shape of the split ring resonator 100 is selected based on (a) the ability to tessellate over a surface with the goal of maximizing the area utilization, and (b) the creation of a maximum possible area since the gain is proportional to its area.

[0092] According to various embodiments, the condition for tessellation may be determined as

$$\sum_{i=1}^m \theta_i = 2\pi \quad (3)$$

[0093] where θ_i is the interior angle of the vertices,

[0094] m is the number of vertices at a point.

[0095] For a n-sided regular polygon,

$$\theta_1 = \theta_2 = \theta_3 = \dots = \theta_n$$

$$\therefore m\theta_n = 2\pi$$

$$m \frac{\pi}{n} (n-2) = 2\pi$$

$$(n-2)(m-2) = 4 \quad (4)$$

[0096] As the integer factors of 4 are 1, 2, and 4,

[0097] when $n=3, m=6 \Rightarrow$ Equilateral Triangle

[0098] when $n=4, m=4 \Rightarrow$ Square

[0099] when $n=6, m=3 \Rightarrow$ Regular Hexagon

[00100] Accordingly, these are the three regular shapes that can be tessellated as determined according to various embodiments. Constraining to regular polygons that can be tessellated, among the possible geometries of square, equilateral triangle, and regular hexagon, the area of regular hexagon is the largest at $(3\sqrt{3}/8)R^2$ (where R is the maximum dimension). The areas of square and equilateral triangle are $(1/2)R^2$ and $(\sqrt{3}/4)R^2$, respectively. This gives the regular hexagon an area that is 1.3 times that of the equilateral triangle and 1.5 times that of the square.

[00101] For a typical split ring resonator (i.e. a single split ring resonator having one split), the resonant frequency (f) is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

[00102] wherein L is the inductance and C is the capacitance of the resonator/antenna.

[00103] Fig. 4(a) shows a single split ring resonator 400, which is an ESA. The single split ring resonator 400 includes a hexagonal split ring 410, also referred to as a hexagonal folded dipole or a hexagonal metaresonator. The hexagonal split ring 410 includes two through-hole vias 402 forming a split or gap 404 at the bottom of the hexagonal folded dipole to connect to the back of the PCB for component placement or feed points. There is a split or gap 406 at the top of the hexagonal split ring 410, similar to a typical split ring resonator. The top split 406 acts as a capacitor, and the bottom split 404 acts as an unintentional capacitor meant for the feed points and providing a certain amount of capacitive effects for the metaresonator 400. The resonant frequency of the single split ring resonator 400 is calculated as

$$f = \frac{1}{2\pi} \sqrt{\frac{C_T + C_B}{L^2 C_T^2 C_B}} \quad (6)$$

[00104] wherein C_T and C_B are the capacitances for the top gap 406 and the bottom gap 404, respectively. L is the inductance.

[00105] Due to the difference in the separation of the traces, the capacitance at the top is greater than the capacitance at the bottom in the single split ring resonator 400. Furthermore, by assuming that the sum of the capacitances of the top and bottom gaps are greater than the capacitance due to the bottom gap, the resonant frequency of the single split ring resonator 400 can be simplified as

$$f = \frac{1}{2\pi} \frac{1}{\sqrt[4]{C_B}} \frac{1}{\sqrt{L}} \frac{1}{\sqrt[4]{C_T}} \quad (7)$$

[00106] Comparing equations (5) and (7), and assuming $\frac{1}{\sqrt[4]{C_B}}$ is a constant term that has a multiplying effect on the resonant frequency, the effect of the $\frac{1}{\sqrt[4]{C_T}}$ term in equation (7) lowers the resonant frequency much more than the $\frac{1}{\sqrt{C}}$ term in equation (5). This implies that the resonant frequency can be lowered by increasing L and/or C_T . Therefore, the resonant frequency of an electrically small dipole can be lowered by increasing the reactance and/or by increasing the coupling.

[00107] Fig. 4(b) shows a S11 (return loss/reflection coefficient) plot 450 of the hexagonal metaresonator 400 of Fig. 4(a).

[00108] The performance of the metaresonator 400 was simulated in CST® software based on IPC Class 2 PCB standard. A minimum gap separation of about 0.0889mm (3.5 mils) for the top gap was simulated with a minimum trace width of about 0.127mm (5 mils), looking for a satisfactory S11 at the center frequency of 2.442 GHz. However, as shown in Fig. 4(b), even after software optimization, the hexagonal metaresonator 400 is not able to resonate sufficiently at 2.45GHz. For good resonance, the S11 needs to have a value of less than -16dB.

[00109] Fig. 5(a) shows a front view of a metamaterial split ring resonator 500 according to various embodiments. Fig. 5(b) shows a back view 550 of the metamaterial split ring resonator 500 according to various embodiments. The metamaterial split ring resonator 500 of Fig. 5(a) and 5(b) is similar to the metamaterial split ring resonator 100 of Fig. 1 above. Various embodiments of the metamaterial split ring resonator 100 of Fig.

1 above is analogously valid for the metamaterial split ring resonator 500 of Fig. 5(a) and 5(b), and vice versa.

[00110] The metamaterial split ring resonator 500 as shown in Fig. 5(a) may be formed in a top surface of a substrate (e.g. a PCB board), and may include a first split ring 510 including a first split 512 at a first edge 502 of the first split ring 510 and a second split 514 at a second edge 504 of the first split ring 510. The first edge 502 is opposite to the second edge 504. Two through-hole vias 515 are provided at the two ends of the second split 514. The metamaterial split ring resonator may further include a second split ring 520 inside the first split ring 510 and concentric with the first split ring 510, wherein the second split ring 520 includes a third split 522 at a first edge 532 of the second split ring 520 adjacent to the first edge 502 of the first split ring 510. A second edge 534 of the second split ring 520 adjacent to the second edge 504 of the first split ring 510 may have one or more locally curved portions 535, complementary to and spaced apart from the contour of the two through-hole vias 515 of the first split ring 510, as shown in Fig. 5(a). The first split ring 510 includes a first pair of stubs 516 extending inwardly from the first split 512, and the second split ring 520 includes a second pair of stubs 526 extending inwardly from the third split 522. In the back view 550 of Fig. 5(b), the two through hole vias 515 can be seen which may be on the bottom side of the substrate.

[00111] According to the embodiments of Fig. 5(a), a CSRR 520 is added into the SRR 510 to load the hexagonal metaresonator to allow it resonate at a lower frequency which considers it an ESA. The additional four stubs 516, 526 further increase the loading. More importantly, the four stubs facilitate fine tuning of the resonant frequency.

[00112] According to the embodiments of Fig. 5(a), the stubbed CSRR 520 is inserted to the basic structure 400 of Fig. 4(a) using a loading method, in order to improve the S11 at the desired center frequency. This type of antenna is termed metaresonator. This loading method adds more coupling which improves the matching of the ESA at the desired frequency.

[00113] Fig. 6 shows a diagram 600 comparing simulated S11 results of metaresonators in different shapes. Simulated S11 results 640 of the ESA 400 of Fig. 4(a) and simulated S11 results 650 of the ESA 500 of Fig. 5(a) are shown in Fig. 6. The

metaresonator ESA 500 can achieve a S11 of -26 dB compared to a S11 of -5 dB achieved by the single folded dipole ESA 400.

[00114] Based on the better performance of the simulated metaresonator 500 of Fig. 5(a), and keeping the maximum dimension the same for metaresonators of various shapes, simulated S11 results 660 of a triangular metaresonator and simulated S11 results 670 of a squared metaresonator are also compared in Fig. 6. The triangular and square metaresonators may have similar structure as the hexagonal metaresonator 500, and may include stubbed inner and outer rings similar to the hexagonal metaresonator 500. The results shown in Fig. 6 indicate that, the hexagonal metaresonator 500 has better S11 at the center frequency compared to the triangular and square metaresonators. In addition, simulated gain shows that the hexagonal metaresonator 500 has the highest gain at -15.4 dB to -17.4 dB, compared to -21.7 dB to -22.4 dB and -15.6 dB to -17.9 dB for the triangular and square metaresonators, respectively.

[00115] Therefore, the stubbed hexagonal metaresonator 500 presented the best performance among the three shapes, and may be used to form the unit cell for a metaresonator array (e.g. the metaresonator array 200 of Fig. 2) according to various embodiments above. In other embodiments, the triangular or square metaresonators may also be used as the unit cell for a metaresonator array. The metaresonators 500 can be optimized by the addition of stubs varying in length to fine-tune the center frequency, avoiding the shifting on the center frequency of the array compared to the unit cell.

[00116] The optimization was performed in CST® using the in-built optimization algorithms. There is a total of seven optimization algorithms starting from Classic Powell (local optimizer) to Covariance Matrix Adaptation Evolution Strategy (CMA-ES) (global optimizer). To reduce the computation time, a parameter sweep of stub length from 0.1 mm to 2.6 mm is performed first.

[00117] Fig. 7 shows a diagram 700 illustrating the optimization results of S11 response when stub lengths of the hexagonal metaresonator 100, 500 are varied, thereby showing the effects of changing the stub lengths. As shown in Fig. 7, as the stub length varies, the center frequency is shifted at the cost of S11. The resonant frequency is shifted from higher frequencies to lower frequencies as the stub length increases. Although the S11 shows varying values as it moves from the right to the left, the S11 has the best values and there is a good balance concerning S11 and the center frequency for stub

lengths between 0.6 mm to 1.1mm. This shows that by tuning the stub lengths within this range, optimal S11 value can be obtained. Based on this, further optimization using Classic Powell is performed for stub lengths between 0.6 mm to 1.1mm. The results show that the optimal length is 0.775 mm.

[00118] According to various embodiments above, an ESA unit cell, e.g. the metaresonator 100, 500, is provided that can resonate at high frequencies (3 MHz to 30MHz), very high frequencies (30 MHz to 300MHz), ultra high frequencies (300MHz to 3GHz), or super high frequencies (3GHz to 30GHz); where the incoming wavelength is significantly larger than the antenna. In addition, when a plurality of unit elements/cells are arranged in a metaresonator array (e.g. the array 200 of Fig. 2), the resonant frequency of the metaresonator array may be adjustable by adjusting the stub lengths of the metaresonators. Further, the fields of metamaterials (MM), electrically small antenna (ESA), and antenna array are combined to produce the metaresonator array for EM/RF energy harvesting and shielding. These result in an enhanced metaresonator array composite for EM/RF shielding and energy harvesting.

[00119] According to various embodiments, by constraining each element size to be 0.1λ or less, the beneficial effects of ESA, antenna array, and MM are combined, examples of which include DC combining techniques from antenna array, double negative index properties from MM, and lumped model analysis from ESA.

[00120] By having a complementary split ring resonator (CSRR) structure 120, 520 as in the metaresonator 100, 500 of the above embodiments, the single split ring ESA 110, 510 can be made to resonate at a lower frequency than without a CSRR. This is not easily achievable given the constraints of using typical PCB technologies.

[00121] In addition, having the double stubbed hexagonal CSRR 120, 520, the resonant frequency of the metaresonator 100, 500 can be tuned by adjusting the length of the stubs. As such, the metaresonator array, e.g. the array 200 of Fig. 2, can be fine-tuned to the desired operating frequency very accurately.

[00122] Fig. 8(a) shows a CST model of a metaresonator 800 according to various embodiments, and Fig. 8(b) shows a photograph 840 of a fabricated metaresonator 850 according to various embodiments. The metaresonators 800, 850 of Fig. 8(a) and 8(b) are similar to the metamaterial split ring resonator 100 of Fig. 1 and the metamaterial split ring resonator 500 of Fig. 5(a) above. Various embodiments of the metamaterial split ring

resonator 100 of Fig. 1 and the metamaterial split ring resonator 500 of Fig. 5(a) above is analogously valid for the metaresonator 800, 850 of Fig. 8(a) and 8(b), and vice versa.

Table 1 Parameters of the fabricated metaresonator

Parameter	Property	Units
Substrate		
Material	FR4	-
Thickness	0.6 to 1.6	mm
Trace		
Material	copper	-
Thickness	12.7 to 50.8	μm
Width	76.2 to 152.4	μm
Clearance / separation	76.2 to 127	μm
Stub length	0.1 to 1.3	mm
Via		
Separation	1.905	mm
Diameter	0.254	mm
Annular ring diameter	0.508	mm
Clearance	0.127	mm

[00123] The simulated metaresonator 800 may be formed on a substrate 810, for example, a top surface of the substrate 810. Similarly, the fabricated metaresonator 850 is formed on a substrate, for example, a front surface 860 of the substrate. The fabricated metaresonator 850 includes through hole vias 855 at the front surface 860 of the substrate. A back surface 870 of the substrate shows the through hole vias 855 of the metaresonator 850 from the back view. The ruler 880 at the bottom of the photograph 840 indicates that the width of the fabricated metaresonator 850 in this exemplary embodiment is about 1.2cm, and the width of the substrate in this exemplary embodiment is about 1.3cm.

[00124] In order to reduce the cost of fabrication for the fabricated metaresonator 850, standard PCB processes and FR-4 as a substrate are used. As described above, in PCB technologies, there are four classes of printed boards according to the IPC standards. In most cases, Class 2 has a good balance between cost and standard. For the design 850, the trace width of the split ring required in an exemplary embodiment is about 0.127mm with a trace separation of about 0.0889mm, and accordingly Class 2 was selected.

[00125] Accordingly, the unit cell 850 was fabricated using IPC Class 2 standard, as shown in Fig. 8(b). The exemplary values of parameters of the fabricated metaresonator

850 are listed in Table 1, wherein the various parameters are depicted in Fig. 8(a). The parameters of the metaresonator according to various embodiments of this specification may be in any other suitable values or range of values depending on the design need.

[00126] To validate the performance of the metaresonator of various embodiments, a S11 measurement is done using Agilent EA-6884 Vector Network Analyser (VNA) on the fabricated antenna. Fig. 9 shows a photograph 900 depicting the back of the fabricated metaresonator 850 with a RF coaxial cable 910 soldered according to various embodiments. The RF coaxial cable 910 is soldered directly onto the 0402 (1.0mm x 0.5mm) component footprint soldering as shown in Fig. 9. At the back of the antenna, a 0402 component footprint is connected to two through hole vias, which connect to the folded dipole in the front. This pad is an allocation for a diode, which can be used for rectifying RF to DC. For measurements, this serves as feed points for the coaxial cable. The length of the coaxial cable 910 used is 1λ (12.3 cm). It is important to take extreme care during direct soldering of the coaxial cable 910 to the antenna feed point to reduce unintended introduction of reactance into the antenna 850. Only a small amount of solder is used to ensure connectivity.

[00127] Fig. 10 shows a diagram 1000 illustrating the comparison between the simulated and measured results according to various embodiments. S11 was measured using an Agilent EA-6884 Vector Network Analyzer (VNA). The return loss of the simulated result corresponding to the simulated metaresonator 800 shows -8.3 dB, -25.7 dB, and -9.4 dB at channels 1, 7, and 13 respectively, with a 10 dB return loss bandwidth of 2%. For the measured result corresponding to the fabricated metaresonator 850, the return loss is -10.5 dB, -16 dB, and -14.8 dB for channels 1, 7, and 13 respectively, with a 10 dB return loss bandwidth of 3.5%. Both results show good agreement with each other at the extreme channels as well as the center channel, validating the simulation. This also shows that the bandwidth of the antenna is wide enough to cover the WiFi band from channels 1 to 13.

[00128] The experiment results show that a 0.1λ ESA can be made to resonate sufficiently using CSRR loading (concept from MM) according to various embodiments, for conventional PCB technologies fabrication processes. In addition, the four stubs design according to various embodiments further increases the loading while providing a method for fine tuning the antenna.

[00129] Fig. 11 shows radiation gain patterns (unit: dBi) of both simulated and measured antennas 800, 850 according to various embodiments, for two extreme channels at channel 1 (shown in Fig. 11(a) and 11(b)) and channel 13 (Fig. 11(e) and 11(f)) of Wi-Fi, and the center frequency at channel 7 (Fig. 11(c) and 11(d)).

[00130] The measurements are taken in an anechoic chamber with port 1 of the VNA connected to a horn antenna from Vector Telecom (part no. VT22SGAH10NK), and port 2 of the VNA connected to the metaresonator ESA of various embodiments via a coaxial cable. The two antennas are placed at a far field distance of 110 cm apart (the maximum dimension of the horn antenna is 26 cm). The radiation patterns for measurement (shown in solid line) and simulation (shown in dashed line) are in good agreement for all the 3 channels, both for the E-plane (Fig. 11(a), 11(c) and 11(e)) and the H-plane (Fig. 11(b), 11(d), 11(f)). In addition, the radiation patterns show consistency when the frequency changes from channel 1 to 13. The patterns displayed for the three channels are also similar to that of a dipole.

[00131] The experimental results show that the metaresonator antenna according to the embodiments above can operate at the designed Wi-Fi frequency band with good S11 of -16 dB (which corresponds to VSWR (Voltage Standing Wave Ratio) of 1.38). The simulated results of Fig. 6 also show that the gain of the hexagonal metaresonator of various embodiments is the highest among the three types of antenna shape, which is at -15.4 dB to -17.4 dB. One solution to further increase the gain is by increasing the area of the antenna. Therefore, various embodiments below increase the area by tessellating or arranging the unit cell of metaresonator 100, 500, 800, 850 above into an antenna array in order to increase the gain without using impedance transformers.

[00132] Fig. 12(a) shows a CST® model of a metamaterial split ring resonator array 1200 (e.g. similar to the array 200 of Fig. 2) according to various embodiments, also referred to as a metaresonator array or an antenna array. Various embodiments of the array 200 of Fig. 2 are analogously valid for the array 1200, and vice versa. In the embodiments of Fig. 12(a), the orientation of each metaresonator 100 is the same, with spacing between adjacent metaresonators. The metaresonators 100 may be formed on a top layer of a substrate, and include respective through hole vias 1230 for connecting to DC lines 1240 on the bottom layer of the substrate.

[00133] Fig. 12(b) shows a top view 1210 of a fabricated metamaterial split ring resonator array 1250 (e.g. similar to the array 200 of Fig. 2) according to various embodiments. Various embodiments of the array 200 of Fig. 2 are analogously valid for the array 1250, and vice versa. The array 1250 may be fabricated as a planar array on a top surface of a substrate. As shown in Fig. 12(b), the top side of the substrate has seven metaresonators 100, which are linked to a bottom layer of the substrate via two through hole vias 1230 of each metaresonator 100, in the same way as the single metaresonator described in Fig. 5(a).

[00134] Fig. 12(c) shows a bottom view 1220 of the fabricated metamaterial split ring resonator array 1250 according to various embodiments. At the bottom layer of the substrate as shown in Fig. 12(c), each metaresonator is connected via DC lines 1240, as the current can be treated as uniform.

[00135] As each metaresonator 100 has been optimized for 2.4 GHz Wi-Fi band, only the separation distance between adjacent metaresonators and stub lengths need to be optimized. The separation affects the coupling between the metaresonators, while the stub length has the effect of fine shifting of the resonant frequency. This is useful for fine adjustment of the resonant frequency after the array 1200, 1250 is formed, to ensure resonance at the desired frequency.

[00136] The optimized dimensions of this seven-metaresonator array 1200, 1250 retain the same trace width and trace separation for each unit cell, while the cell separation is 2.032mm (80 mils), and the stub length is 0.561mm. The overall dimension of the seven-cell metaresonator array 1200, 1250 is 40 mm x 40 mm x 1.6 mm. A S11 comparison 1300 between the simulated metaresonator array 1200 and the fabricated metaresonator array 1250 according to various embodiments is shown in Fig. 13. The results agree well with each other, showing good S11 values of less than -25 dB (which corresponds to VSWR of 1.12), and a -10 dB fractional bandwidth of 3%.

[00137] Fig. 14 shows gain comparison 1400 between unit element 100 and array 200, 1200, 1250 according to various embodiments. As shown in Fig. 14, the gain of the metaresonator array 200, 1200, 1250 is increased at -5.5 dB to -4.7dB compared to unit element 100 of -15.4 dB to -17.4 dB.

[00138] From the above, it is shown that the ESA metaresonator 100 according to various embodiments can be used as a unit element in an array. Each of the unit elements

are electrically small, which allows them to be interconnected without impedance transformers. Compared to conventional antenna arrays, this metaresonator array design according to various embodiments above does not require a ground plane, which then frees up the bottom side of the PCB for interconnections, thus allowing for greater area utilization on the top side of the PCB.

[00139] Various embodiments above present a construction of 0.1λ ESA that overcomes the problem of fabricating ESA of this dimension for 2.45 GHz using standard PCB technologies and materials. The simulation and experimental results are shown to be in good agreement. To demonstrate the potential of using this ESA as a unit element for antenna array without using impedance transformers, a seven-element array is simulated and fabricated, e.g. in Fig. 12 above. The simulation and experimental results show that by optimizing the element separation distance and stub lengths, the ESA array shows good S11 of less than -25 dB, and gain improvement of up to 12 dB compared to a single unit ESA.

[00140] In various embodiments, the metaresonators may be arranged in a different arrangement from the array 1200, 1250. Fig. 15(a) shows a front view of an arrangement of a metaresonator array 1500 according to various embodiments, and Fig. 15(b) shows a back view 1550 of the metaresonator array 1500.

[00141] In the embodiments of Fig. 15(a), the unit cell of the respective metaresonator 100 (similar to the metamaterial split ring resonator of Fig. 1 above) are tessellated into an array with substantially no gap or spacing between each other. The metaresonators 100 may be formed on a top layer of a substrate, and include respective through hole vias 1530 for connecting to DC lines 1540 on the bottom layer of the substrate. The metaresonators 100 may be arranged in a different orientation, for example, with the stubs of different metaresonators 100 extending along or protruding towards different directions, and located along the outer perimeter or boundary of the array.

[00142] At the bottom layer of the substrate as shown in Fig. 15(b), each metaresonator is connected via DC lines 1540.

[00143] Fig. 16 shows S11 results 1600 of the metaresonator array 1500 according to various embodiments. From Fig. 16, it can be seen that even after tessellating seven unit elements/cells into an array, the resonant frequency can still be at 2.45 GHz. This is achieved by tuning the stub length to fine tune the resonant frequency to the exact value.

[00144] Although the embodiments of Fig. 12 and Fig. 15 show two arrangements of the metaresonator array, it is understood that the metaresonator array may be implemented in any other suitable arrangements based on the shape of each unit cell, and at the same time has the flexibility of adjusting the length of the stubs to maintain good performance of the array. In addition, although the embodiments of Fig. 12 and Fig. 15 show 7 metaresonators arranged in the array, it is understood that any other number of metaresonators may be included in the array.

[00145] According to various embodiments, the metaresonator, the metaresonator array and the energy harvesting apparatus described above have potential commercial applications of EM/RF shielding and energy harvesting in 1) building façade, 2) building interior partitions, walls, ceilings and floors, 3) surfaces, and 4) anechoic chambers, etc.

[00146] In various embodiments, a 2.4 GHz industrial, scientific, and medical radio band (ISM band) is used to demonstrate the concept of EM/RF shielding and energy harvesting. This frequency band is chosen as this spectrum is increasingly getting crowded in buildings. With the future implementation of LTE-U, which also uses this same band for mobile communications, various embodiments can also be used to increase spectrum efficiency by allowing more wireless devices to be connected at the same time.

[00147] According to various embodiments, the element/cell size of the ESA is determined be 0.1λ , which is required to combine the beneficial effects of ESA, antenna array, and MM. As there is a need to fabricate the ESA using conventional low cost PCB technologies, the ESA is insufficient to resonate at a frequency where the element/cell is considered an ESA. Accordingly, a four stubs complementary split ring resonator (CSRR) is proposed to load the ESA for lower frequency operations according to various embodiments. The stubs are also shown to have the ability to fine tune the resonating frequency. This is important when this element/cell is tessellated into an array, as the typical metaresonator array does not have the flexibility of adjusting the frequency after each individual element/cell has been fixed.

[00148] In the following, the metaresonator array according to various embodiments is tested with a router and a signal generator.

[00149] Fig. 17 shows an experimental set up using an off the shelf router 1710 according to various embodiments.

[00150] The off the shelf router 1710 may be an off the shelf WiFi router (e.g., TP-link TL-WR702N). The antenna array 1720 is placed at a far field distance of 55 mm. The antenna array 1720 may be similar to the metaresonator array 200 of Fig. 2 and the metaresonator array 1250 of Fig. 12(b) above. The measured resistance of the antenna is 250Ω . To achieve maximum power transfer, a load 1730 of 250Ω is soldered to the antenna array 1720. The router 1710 is configured to transmit at a maximum power of 20 dBm.

[00151] According to the testing result, the received voltage is 30 mV with a corresponding power of $3.6 \mu\text{W}$. The efficiency of this set up of Fig. 17 is about 0.0003%.

[00152] Fig. 18 shows an experimental set up according to various embodiments using a signal generator 1810, which is connected to an amplifier and a monopole antenna.

[00153] This experiment was conducted using the signal generator 1810 (e.g., -20 dBm), connected to the amplifier 1820 (e.g., 18 dB), and the monopole antenna 1830. The antenna array 1720 same as the antenna array of Fig. 17 is placed at a far field distance of 125 mm. The same load 1730 of 250Ω is used.

[00154] According to the testing result of Fig. 18, the received voltage is 250 mV with a corresponding power of $250 \mu\text{W}$. The efficiency of this set up is about 10%.

[00155] In the testing of Fig. 17 and Fig. 18, the calculations do not include path loss and several assumptions are taken to simplify calculations.

[00156] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.