

TITLE

METAMATERIALS FOR SURFACES AND WAVEGUIDES

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority from provisional application
5 no. 61/091,337 filed August 22, 2008, incorporated herein by reference.

STATEMENT REGARDING FEDERALLY
SPONSORED RESEARCH OR DEVELOPMENT

[0002]

TECHNICAL FIELD

10 **[0003]** The technology herein relates to artificially-structured materials such as
metamaterials, which function as artificial electromagnetic materials. Some
approaches provide surface structures and/or waveguide structures responsive to
electromagnetic waves at radio-frequencies (RF) microwave frequencies, and/or
higher frequencies such as infrared or visible frequencies. In some approaches the
15 electromagnetic responses include negative refraction. Some approaches provide
surface structures that include patterned metamaterial elements in a conducting
surface. Some approaches provide waveguide structures that include patterned
metamaterial elements in one or more bounding conducting surfaces of the
waveguiding structures (e.g. the bounding conducting strips, patches, or planes of
20 planar waveguides, transmission line structures or single plane guided mode
structures).

BACKGROUND AND SUMMARY

[0004] Artificially structured materials such as metamaterials can extend the
electromagnetic properties of conventional materials and can provide novel
25 electromagnetic responses that may be difficult to achieve in conventional materials.

Metamaterials can realize complex anisotropies and/or gradients of electromagnetic parameters (such as permittivity, permeability, refractive index, and wave impedance), whereby to implement electromagnetic devices such as invisibility cloaks (see, for example, J. Pendry et al, "Electromagnetic cloaking method," U.S. Patent App. No. 11/459728, herein incorporated by reference) and GRIN lenses (see, for example, D. R Smith et al, "Metamaterials," U.S. Patent Application No. 11/658358, herein incorporated by reference). Further, it is possible to engineer metamaterials to have negative permittivity and/or negative permeability, e.g. to provide a negatively refractive medium or an indefinite medium (i.e. having tensor-indefinite permittivity and/or permeability; see, for example, D. R. Smith et al, "Indefinite materials," U.S. Patent Application No. 10/525191, herein incorporated by reference).

[0005] The basic concept of a "negative index" transmission line, formed by exchanging the shunt capacitance for inductance and the series inductance for capacitance, is shown, for example, in Pozar, *Microwave Engineering* (Wiley 3d Ed.).

The transmission line approach to metamaterials has been explored by Itoh and Caloz (UCLA) and Eleftheriades and Balmain (Toronto). See for example Elek et al, "A two-dimensional uniplanar transmission-line metamaterial with a negative index of refraction", *New Journal of Physics* (Vol. 7, Issue 1 pp. 163 (2005); and US Patent No. 6,859,114.

[0006] The transmission lines (TLs) disclosed by Caloz and Itoh are based on swapping the series inductance and shunt capacitance of a conventional TL to obtain the TL equivalent of a negative index medium. Because shunt capacitance and series inductance always exist, there is always a frequency dependent dual behavior of the TLs that gives rise to a "backward wave" at low frequencies and a typical forward wave at higher frequencies. For this reason, Caloz and Itoh have termed their metamaterial TL a "composite right/left handed" TL, or CRLH TL. The CRLH TL is formed by the use of lumped capacitors and inductors, or equivalent circuit elements, to produce a TL that functions in one dimension. The CRLH TL concept has been extended to two dimensional structures by Caloz and Itoh, and by Grbic and Eleftheriades.

[0007] Use of a complementary split ring resonator (CSRR) as a microstrip circuit element was proposed in F. Falcone et al., "Babinet principle applied to the design of metasurfaces and metamaterials," Phys. Rev. Lett. V93, Issue 19, 197401. The CSRR was demonstrated as a filter in the microstrip geometry by the same group. See e.g., Marques et al, "Ab initio analysis of frequency selective surfaces based on conventional and complementary split ring resonators", Journal of Optics A: Pure and Applied Optics, Volume 7, Issue 2, pp. S38-S43 (2005), and Bonache et al., "Microstrip Bandpass Filters With Wide Bandwidth and Compact Dimensions" (Microwave and Optical Tech. Letters (46:4, p. 343 2005). The use of CSRRs as patterned elements in the ground plane of a microstrip was explored. These groups demonstrated the microstrip equivalent of a negative index medium, formed using CSRRs patterned in the ground plane and capacitive breaks in the upper conductor. This work was extended to coplanar microstrip lines as well.

[0008] A split-ring resonator (SRR) substantially responds to an out-of-plane magnetic field (i.e. directed along the axis of the SRR). The complementary SRR (CSRR) , on the other hand, substantially responds to an out-of-plane *electric* field (i.e. directed along the CSRR axis). The CSRR may be regarded as the "Babinet" dual of the SRR and embodiments disclosed herein may include CSRR elements embedded in a conducting surface, e.g. as shaped apertures, etchings, or perforation of a metal sheets. In some applications as disclosed herein, the conducting surface with embedded CSRR elements is a bounding conductor for a waveguide structure such as a planar waveguide, microstrip line, etc.

[0009] While split-ring resonators (SRRs) substantially couple to an out-of-plane magnetic field, some metamaterial applications employ elements that substantially couple to an *in-plane electric* field. These alternative elements may be referred to as electric LC (ELC) resonators, and exemplary configurations are depicted in D. Schurig et al, "Electric-field coupled resonators for negative permittivity metamaterials," Appl. Phys. Lett 88, 041109 (2006). While the electric LC (ELC) resonator substantially couples to an in-plane electric field, the *complementary* electric LC (CELC) resonator substantially responds to an in-plane *magnetic* field. The CELC resonator may be regarded the "Babinet" dual of the ELC resonator, and

embodiments disclosed herein may include CELC resonator elements (alternatively or additionally to CSRR elements) embedded in a conducting surface, e.g. as shaped apertures, etchings, or perforations of a metal sheet. In some applications as disclosed herein, a conducting surface with embedded CSRR and/or CELC elements is a bounding conductor for a waveguide structure such as a planar waveguide, microstrip line, etc.

[0010] Some embodiments disclosed herein employ complementary electric LC (CELC) metamaterial elements to provide an effective permeability for waveguide structures. In various embodiments the effective (relative) permeability may be greater than one, less than one but greater than zero, or less than zero. Alternatively or additionally, some embodiments disclosed herein employ complementary split-ring-resonator (CSRR) metamaterial elements to provide an effective permittivity for planar waveguide structures. In various embodiments the effective (relative) permittivity may be greater than one, less than one but greater than zero, or less than zero

[0011] Exemplary non-limiting features of various embodiments include:

- Structures for which an effective permittivity, permeability, or refractive index is near zero
- Structures for which an effective permittivity, permeability, or refractive index is less than zero
- Structures for which an effective permittivity or permeability is an indefinite tensor (i.e. having both positive and negative eigenvalues)
- Gradient structures, e.g. for beam focusing, collimating, or steering
- Impedance matching structures, e.g. to reduce insertion loss
- Feed structures for antenna arrays
- Use of complementary metamaterial elements such as CELCs and CSRRs to substantially independently configure the magnetic and electric

responses, respectively, of a surface or waveguide, e.g. for purposes of impedance matching, gradient engineering, or dispersion control

- Use of complementary metamaterial elements having adjustable physical parameters to provide devices having correspondingly adjustable electromagnetic responses (e.g. to adjust a steering angle of a beam steering device or a focal length of a beam focusing device)
- Surface structures and waveguide structures that are operable at RF, microwave, or even higher frequencies (e.g. millimeter, infrared, and visible wavelengths)

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BRIEF DESCRIPTION OF THE DRAWINGS

[0012] These and other features and advantages will be better and more completely understood by referring to the following detailed description of exemplary non-limiting illustrative implementations in conjunction with the drawings of which:

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[0013] Figures 1-1D depict a wave-guided complementary ELC (magnetic response) structure (Figure 1) and associated plots of effective permittivity, permeability, wave impedance, and refractive index (Figures 1A-1D);

[0014] Figures 2-2D depict a wave-guided complementary SRR (electric response) structure (Figure 2) and associated plots of effective permittivity, permeability, wave impedance, and refractive index (Figures 2A-2D);

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[0015] Figures 3-3D depict a wave-guided structure with both CSRR and CELC elements (e.g. to provide an effective negative index) (Figure 3) and associated plots of effective permittivity, permeability, wave impedance, and refractive index (Figures 3A-3D);

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[0016] Figures 4-4D depict a wave-guided structure with both CSRR and CELC elements (e.g. to provide an effective negative index) (Figure 4) and associated plots of effective permittivity, permeability, wave impedance, and refractive index (Figures 4A-4D);

[0017] Figures 5-5D depict a microstrip complementary ELC structure (Figure 5) and associated plots of effective permittivity, permeability, wave impedance, and refractive index (Figures 5A-5D);

5 [0018] Figures 6-6D are depict a microstrip structure with both CSRR and CELC elements (e.g. to provide an effective negative index) (Figure 6) and associated plots of effective permittivity, permeability, wave impedance, and refractive index (Figures 6A-6D);

[0019] Figure 7 depicts an exemplary CSRR array as a 2D planar waveguide structure;

10 [0020] Figure 8-1 depicts retrieved permittivity and permeability of a CSRR element, and Figure 8-2 depicts the dependence of the retrieved permittivity and permeability on a geometrical parameter of the CSRR element;

[0021] Figures 9-1, 9-2 depict field data for 2D implementations of the planar waveguide structure for beam-steering and beam-focusing applications, respectively;

15 [0022] Figures 10-1, 10-2 depict an exemplary CELC array as a 2D planar waveguide structure providing an indefinite medium; and

[0023] Figures 11-1, 11-2 depict a waveguide based gradient index lens deployed as a feed structure for an array of patch antennas.

DETAILED DESCRIPTION

20 [0024] Various embodiments disclosed herein include "complementary" metamaterial elements, which may be regarded as Babinet complements of original metamaterial elements such as split ring resonators (SRRs) and electric LC resonators (ELCs).

25 [0025] The SRR element functions as an artificial magnetic dipolar "atom," producing a substantially magnetic response to the magnetic field of an electromagnetic wave. Its Babinet "dual," the complementary split ring resonator (CSRR), functions as an *electric* dipolar "atom" embedded in a conducting surface and

producing a substantially electric response to the electric field of an electromagnetic wave. While specific examples are described herein that deploy CSRR elements in various structures, other embodiments may substitute alternative elements. For example, any substantially planar conducting structure having a substantially magnetic response to an out-of-plane magnetic field (hereafter referred to as a “M-type element,” the SRR being an example thereof) may define a complement structure (hereafter a “complementary M-type element,” the CSRR being an example thereof), which is a substantially-equivalently-shaped aperture, etching, void, etc. within a conducting surface. The complementary M-type element will have a Babinet-dual response, i.e. a substantially electric response to an out-of-plane electric field. Various M-type elements (each defining a corresponding complementary M-type element) may include: the aforementioned split ring resonators (including single split ring resonators (SSRRs), double split ring resonators (DSRRs), split-ring resonators having multiple gaps, etc.), omega-shaped elements (cf. C.R. Simovski and S. He, arXiv:physics/0210049), cut-wire-pair elements (cf. G. Dolling et al, Opt. Lett. 30, 3198 (2005)), or any other conducting structures that are substantially magnetically polarized (e.g. by Faraday induction) in response to an applied magnetic field.

[0026] The ELC element functions as an artificial electric dipolar “atom,” producing a substantially electric response to the electric field of an electromagnetic wave. Its Babinet “dual,” the complementary electric LC (CELC) element, functions as a *magnetic* dipolar “atom” embedded in a conducting surface and producing a substantially magnetic response to the magnetic field of an electromagnetic wave. While specific examples are described herein that deploy CELC elements in various structures, other embodiments may substitute alternative elements. For example, any substantially planar conducting structure having a substantially electric response to an in-plane electric field (hereafter referred to as a “E-type element,” the ELC element being an example thereof) may define a complement structure (hereafter a “complementary E-type element,” the CELC being an example thereof), which is a substantially-equivalently-shaped aperture, etching, void, etc. within a conducting surface. The complementary E-type element will have a Babinet-dual response, i.e. a substantially magnetic response to an in-plane magnetic field. Various E-type elements (each defining a corresponding complementary E-type element) may

include: capacitor-like structures coupled to oppositely-oriented loops (as in Figures 1, 3, 4, 5, 6, and 10-1, with other exemplary varieties depicted in D. Schurig et al, "Electric-field-coupled resonators for negative permittivity metamaterials," Appl. Phys. Lett. 88, 041109 (2006) and in H.-T. Cen et al, "Complementary planar terahertz metamaterials," Opt. Exp. 15, 1084 (2007)), closed-ring elements (cf. R. Liu et al, "Broadband gradient index optics based on non-resonant metamaterials," unpublished; see attached Appendix), I-shaped or "dog-bone" structures (cf. R. Liu et al, "Broadband ground-plane cloak," Science 323, 366 (2009)), cross-shaped structures (cf. H.-T. Cen et al, previously cited), or any other conducting structures that are substantially electrically polarized in response to an applied electric field. In various embodiments, a complementary E-type element may have a substantially isotropic magnetic response to in-plane magnetic fields, or a substantially anisotropic magnetic response to in-plane magnetic fields.

[0027] While an M-type element may have a substantial (out-of-plane) magnetic response, in some approaches an M-type element may additionally have an (in-plane) electric response that is also substantial but of lesser magnitude than (e.g. having a smaller susceptibility than) the magnetic response. In these approaches, the corresponding complementary M-type element will have a substantial (out-of-plane) electric response, and additionally an (in-plane) magnetic response that is also substantial but of lesser magnitude than (e.g. having a smaller susceptibility than) the electric response. Similarly, while an E-type element may have a substantial (in-plane) electric response, in some approaches an E-type element may additionally have an (out-of-plane) magnetic response that is also substantial but of lesser magnitude than (e.g. having a smaller susceptibility than) the electric response. In these approaches, the corresponding complementary E-type element will have a substantial (in-plane) magnetic response, and additionally an (out-of-plane) electric response that is also substantial but of lesser magnitude than (e.g. having a smaller susceptibility than) the magnetic response.

[0028] Some embodiments provide a waveguide structure having one or more bounding conducting surfaces that embed complementary elements such as those described previously. In a waveguide context, quantitative assignment of quantities

typically associated with volumetric materials—such as the electric permittivity, magnetic permeability, refractive index, and wave impedance—may be defined for planar waveguides and microstrip lines patterned with the complementary structures. For example, one or more complementary M-type elements such as CSRRs, patterned in one or more bounding surfaces of a waveguide structure, may be characterized as having an effective electric permittivity. Of note, the effective permittivity can exhibit both large positive and negative values, as well as values between zero and unity, inclusive. Devices can be developed based at least partially on the range of properties exhibited by the M-type elements, as will be described.

The numerical and experimental techniques to quantitatively make this assignment are well-characterized.

[0029] Alternatively or additionally, in some embodiments complementary E-type elements such as CELCs, patterned into a waveguide structure in the same manner as described above, have a magnetic response that may be characterized as an effective magnetic permeability. The complementary E-type elements thus can exhibit both large positive and negative values of the effective permeability, as well as effective permeabilities that vary between zero and unity, inclusive. (throughout this disclosure, real parts are generally referred to in the descriptions of the permittivity and permeability for both the complementary E-type and complementary M-type structures, except where context dictates otherwise as shall be apparent to one of skill in the art) Because both types of resonators can be implemented in the waveguide context, virtually any effective material condition can be achieved, including negative refractive index (both permittivity and permeability less than zero), allowing considerable control over waves propagating through these structures. For example, some embodiments may provide effective constitutive parameters substantially corresponding to a transformation optical medium (as according to the method of transformation optics, e.g. as described in J. Pendry et al, "Electromagnetic cloaking method," U.S. Patent App. No. 11/459728).

[0030] Using a variety of combinations of the complementary E- and/or M-type elements, a wide variety of devices can be formed. For example, virtually all of the devices that have been demonstrated by Caloz and Itoh using CRLH TLs have

analogs in the waveguiding metamaterial structures described here. Most recently, Silvereinha and Engheta proposed an interesting coupler based on creating a region in which the effective refractive index (or propagation constant) is nearly zero (CITE). The equivalent of such a medium can be created by the patterning of complementary E- and/or M-type elements into the bounding surfaces of a waveguide structure. The Figures show and describe exemplary illustrative non-limiting realizations of the zero index coupler and other devices with the use of patterned waveguides and several depictions as to how exemplary non-limiting structures may be implemented.

[0031] Figure 1 shows an exemplary illustrative non-limiting wave-guided complementary ELC (magnetic response) structure, and Figures 1A-1D show associated exemplary plots of the effective index, wave impedance, permittivity and permeability. While the depicted example shows only a single CELC element, other approaches provide a plurality of CELC (or other complementary E-type) elements disposed on one or more surfaces of a waveguide structure.

[0032] Figure 2 shows an exemplary illustrative non-limiting wave-guided complementary SRR (electric response) structure, and Figures 2A-2D show associated exemplary plots of the effective index, wave impedance, permittivity and permeability. While the depicted example shows only a single CSRR element, other approaches provide a plurality of CSRR elements (or other complementary M-type) elements disposed on one or more surfaces of a waveguide structure.

[0033] Figure 3 shows an exemplary illustrative non-limiting wave-guided structure with both CSRR and CELC elements (e.g. to provide an effective negative index) in which the CSRR and CELC are patterned on opposite surfaces of a planar waveguide, and Figures 3A-3D show associated exemplary plots of the effective index, wave impedance, permittivity and permeability. While the depicted example shows only a single CELC element on a first bounding surface of a waveguide and a single CSRR element on a second bounding surface of the waveguide, other approaches provide a plurality of complementary E- and/or M-type elements disposed on one or more surfaces of a waveguide structure.

[0034] Figure 4 shows an exemplary illustrative non-limiting wave-guided structure with both CSRR and CELC elements (e.g. to provide an effective negative index) in which the CSRR and CELC are patterned on the same surface of a planar waveguide, and Figures 4A-4D show associated exemplary plots of the effective index, wave impedance, permittivity and permeability. While the depicted example shows only a single CELC element and a single CSRR element on a first bounding surface of a waveguide, other approaches provide a plurality of complementary E- and/or M-type elements disposed on one or more surfaces of a waveguide structure.

[0035] Figure 5 shows an exemplary illustrative non-limiting microstrip complementary ELC structure, and Figures 5A-5D show associated exemplary plots of the effective index, wave impedance, permittivity and permeability. While the depicted example shows only a single CELC element on the ground plane of a microstrip structure, other approaches provide a plurality of CELC (or other complementary E-type) elements disposed on one or both of the strip portion of the microstrip structure or the ground plane portion of the microstrip structure.

[0036] Figure 6 shows an exemplary illustrative non-limiting micro-strip line structure with both CSRR and CELC elements (e.g. to provide an effective negative index), and Figures 6A-6D show associated exemplary plots of the effective index, wave impedance, permittivity and permeability. While the depicted example shows only a single CSRR element and two CELC elements on the ground plane of a microstrip structure, other approaches provide a plurality of complementary E- and/or M-type elements disposed on one or both of the strip portion of the microstrip structure or the ground plane portion of the microstrip structure.

[0037] Figure 7 illustrates the use of a CSRR array as a 2D waveguide structure. In some approaches a 2D waveguide structure may have bounding surfaces (e.g. the upper and lower metal plates depicted in Figure 7) that are patterned with complementary E- and/or M-type elements to implement functionality such as impedance matching, gradient engineering, or dispersion control.

[0038] As an example of gradient engineering, the CSRR structure of Figure 7 has been utilized to form both gradient index beam-steering and beam-focusing

structures. Figure 8-1 illustrates a single exemplary CSRR and the retrieved permittivity and permeability corresponding to the CSRR (in the waveguide geometry). By changing parameters within the CSRR design (in this case a curvature of each bend of the CSRR), the index and/or the impedance can be tuned, as shown in Figure 8-2.

[0039] A CSRR structure laid out as shown in Figure 7, with a substantially linear gradient of refractive index imposed along the direction transverse to the incident guided beam, produces an exit beam that is steered to an angle different from that of the incident beam. Figure 9-1 shows exemplary field data taken on a 2D implementation of the planar waveguide beam-steering structure. The field mapping apparatus has been described in considerable detail in the literature [B. J. Justice, J. J. Mock, L. Guo, A. Degiron, D. Schurig, D. R. Smith, "Spatial mapping of the internal and external electromagnetic fields of negative index metamaterials," *Optics Express*, vol. 14, p. 8694 (2006)]. Likewise, implementing a parabolic refractive index gradient along the direction transverse to the incident beam within the CSRR array produces a focusing lens, e.g. as shown in Figure 9-2. More generally, a transverse index profile that is a concave function (parabolic or otherwise) will provide a positive focusing effect, such as depicted in Figure 9-2 (corresponding to a positive focal length); a transverse index profile that is a convex function (parabolic or otherwise) will provide a negative focusing effect (corresponding to a negative focal length, e.g. to receive a collimated beam and transmit a diverging beam). For approaches wherein the metamaterial elements include adjustable metamaterial elements (as discussed below), embodiments may provide an apparatus having an electromagnetic function (e.g. beam steering, beam focusing, etc.) that is correspondingly adjustable. Thus, for example, a beam steering apparatus may be adjusted to provide at least first and second deflection angles; a beam focusing apparatus may be adjusted to provide at least first and second focal lengths, etc. An example of a 2D medium formed with CELCs is shown in Figures 10-1, 10-2. Here, an in-plane anisotropy of the CELCs is used to form an 'indefinite medium,' in which a first in-plane component of the permeability is negative while another in-plane component is positive. Such a medium produces a partial refocusing of waves from a line source, as shown in the experimentally obtained field map of Figure 10-2. The focusing properties of a bulk

indefinite medium have previously been reported [D. R. Smith, D. Schurig, J. J. Mock, P. Kolinko, P. Rye, "Partial focusing of radiation by a slab of indefinite media," Applied Physics Letters, vol. 84, p. 2244 (2004)]. The experiments shown in this set of figures validate the design approach, and show that waveguide metamaterial elements can
5 be produced with sophisticated functionality, including anisotropy and gradients.

[0040] In Figures 11-1 and 11-2, a waveguide-based gradient index structure (e.g. having boundary conductors that include complementary E- and/or M-type elements, as in Figures 7 and 10-1) is disposed as a feed structure for an array of patch antennas. In the exemplary embodiment of Figures 11-1 and 11-2, the feed
10 structure collimates waves from a single source that then drive an array of patch antennas. This type of antenna configuration is well known as the Rotman lens configuration. In this exemplary embodiment, the waveguide metamaterial provides an effective gradient index lens within a planar waveguide, by which a plane wave can be generated by a point source positioned on the focal plane of the gradient index lens,
15 as illustrated by the "feeding points" in Figure 11-2. For the Rotman Lens antenna, one can place multiple feeding points on the focal plane of the gradient index metamaterial lens and connect antenna elements to the output of the waveguide structure as shown in Figure 11-1. From well known optics theory, the phase difference between each antenna will depend on the feed position of the source, so
20 that phased-array beam forming can be implemented. Figure 11-2 is a field map, showing the fields from a line source driving the gradient index planar waveguide metamaterial at the focus, resulting in a collimated beam. While the exemplary feed structure of Figures 11-1 and 11-2 depicts a Rotman-lens type configuration for which the antenna phase differences are substantially determined by the location of the
25 feeding point, in other approaches the antenna phase differences are determined by fixing the feeding point and adjusting the electromagnetic properties (and therefore the phase propagation characteristics of) the gradient index lens (e.g. by deploying adjustable metamaterial elements, as discussed below), while other embodiments may combine both approaches (i.e. adjustment of both the feeding point position and
30 the lens parameters to cumulatively achieve the desired antenna phase differences).

[0041] In some approaches, a waveguide structure having an input port or input region for receiving electromagnetic energy may include an impedance matching layer (IML) positioned at the input port or input region, e.g. to improve the input insertion loss by reducing or substantially eliminating reflections at the input port or input region. Alternatively or additionally, in some approaches a waveguide structure having an output port or output region for transmitting electromagnetic energy may include an impedance matching layer (IML) positioned at the output port or output region, e.g. to improve the output insertion loss by reducing or substantially eliminating reflections at the output port or output region. An impedance matching layer may have a wave impedance profile that provides a substantially continuous variation of wave impedance, from an initial wave impedance at an external surface of the waveguide structure (e.g. where the waveguide structure abuts an adjacent medium or device) to a final wave impedance at an interface between the IML and a gradient index region (e.g. that provides a device function such as beam steering or beam focusing). In some approaches the substantially continuous variation of wave impedance corresponds to a substantially continuous variation of refractive index (e.g. where turning an arrangement of one species of element adjusts both an effective refractive and an effective wave impedance according to a fixed correspondence, such as depicted in Figure 8-2), while in other approaches the wave impedance may be varied substantially independently of the refractive index (e.g. by deploying both complementary E- and M-type elements and independently turning the arrangements of the two species of elements to correspondingly independently tune the effective refractive index and the effective wave impedance).

[0042] While exemplary embodiments provide spatial arrangements of complementary metamaterial elements having varied geometrical parameters (such as a length, thickness, curvature radius, or unit cell dimension) and correspondingly varied individual electromagnetic responses (e.g. as depicted in Figure 8-2), in other embodiments other physical parameters of the complementary metamaterial elements are varied (alternatively or additionally to varying the geometrical parameters) to provide the varied individual electromagnetic responses. For example, embodiments may include complementary metamaterial elements (such as CSRRs or CELCs) that are the complements of original metamaterial elements that include capacitive gaps,

and the complementary metamaterial elements may be parameterized by varied capacitances of the capacitive gaps of the original metamaterial elements.

Equivalently, noting that from Babinet's theorem a capacitance in an element (e.g. in the form of a planar interdigitated capacitor having a varied number of digits and/or varied digit length) becomes an inductance in the complement thereof (e.g. in the form of a meander line inductor having a varied number of turns and/or varied turn length), the complementary elements may be parameterized by varied *inductances* of the complementary metamaterial elements. Alternatively or additionally, embodiments may include complementary metamaterial elements (such as CSRRs or CELCs) that are the complements of original metamaterial elements that include inductive circuits, and the complementary metamaterial elements may be parameterized by varied inductances of the inductive circuits of the original metamaterial elements.

Equivalently, noting that from Babinet's theorem an inductance in an element (e.g. in the form of a meander line inductor having a varied number of turns and/or varied turn length) becomes a capacitance in the complement thereof (e.g. in the form of a planar interdigitated capacitor having a varied number of digits and/or varied digit length), the complementary elements may be parameterized by varied *capacitances* of the complementary metamaterial elements. Moreover, a substantially planar metamaterial element may have its capacitance and/or inductance augmented by the attachment of a lumped capacitor or inductor. In some approaches, the varied physical parameters (such as geometrical parameters, capacitances, inductances) are determined according to a regression analysis relating electromagnetic responses to the varied physical parameters (c.f. the regression curves in Figure 8-2)

[0043] In some embodiments the complementary metamaterial elements are adjustable elements, having adjustable physical parameters corresponding to adjustable individual electromagnetic responses of the elements. For example, embodiments may include complementary elements (such as CSRRs) having adjustable capacitances (e.g. by adding varactor diodes between the internal and external metallic regions of the CSRRs, as in A. Velez and J. Bonarche, "Varactor-loaded complementary split ring resonators (VLCSRR) and their application to tunable metamaterial transmission lines," IEEE Microw. Wireless Compon. Lett. 18, 28 (2008)). In another approach, for waveguide embodiments having an upper and a

lower conductor (e.g. a strip and a ground plane) with an intervening dielectric substrate, complementary metamaterial elements embedded in the upper and/or lower conductor may be adjustable by providing a dielectric substrate having a nonlinear dielectric response (e.g. a ferroelectric material) and applying a bias voltage between the two conductors. In yet another approach, a photosensitive material (e.g. a semiconductor material such as GaAs or n-type silicon) may be positioned adjacent to a complementary metamaterial element, and the electromagnetic response of the element may be adjustable by selectively applying optical energy to the photosensitive material (e.g. to cause photodoping). In yet another approach, a magnetic layer (e.g. of a ferrimagnetic or ferromagnetic material) may be positioned adjacent to a complementary metamaterial element, and the electromagnetic response of the element may be adjustable by applying a bias magnetic field (e.g. as described in J. Gollub et al, "Hybrid resonant phenomenon in a metamaterial structure with integrated resonant magnetic material," arXiv:0810.4871 (2008)). While exemplary embodiments herein may employ a regression analysis relating electromagnetic responses to geometrical parameters (cf. the regression curve in Figure 8-2), embodiments with adjustable elements may employ a regression analysis relating electromagnetic responses to adjustable physical parameters that substantially correlate with the electromagnetic responses.

[0044] In some embodiments with adjustable elements having adjustable physical parameters, the adjustable physical parameters may be adjustable in response to one or more external inputs, such as voltage inputs (e.g. bias voltages for active elements), current inputs (e.g. direct injection of charge carriers into active elements), optical inputs (e.g. illumination of a photoactive material), or field inputs (e.g. bias electric/magnetic fields for approaches that include ferroelectrics/ferromagnets). Accordingly, some embodiments provide methods that include determining respective values of adjustable physical parameters (e.g. by a regression analysis), then providing one or more control inputs corresponding to the determined respective values. Other embodiments provide adaptive or adjustable systems that incorporate a control unit having circuitry configured to determine respective values of adjustable physical parameters (e.g. by a regression analysis)

and/or provide one or more control inputs corresponding to determined respective values.

[0045] While some embodiments employ a regression analysis relating electromagnetic responses to physical parameters (including adjustable physical parameters), for embodiments wherein the respective adjustable physical parameters are determined by one or more control inputs, a regression analysis may directly relate the electromagnetic responses to the control inputs. For example, where the adjustable physical parameter is an adjustable capacitance of a varactor diode as determined from an applied bias voltage, a regression analysis may relate electromagnetic responses to the adjustable capacitance, or a regression analysis may relate electromagnetic responses to the applied bias voltage.

[0046] While some embodiments provide substantially narrow-band responses to electromagnetic radiation (e.g. for frequencies in a vicinity of one or more resonance frequencies of the complementary metamaterial elements), other embodiments provide substantially broad-band responses to electromagnetic radiation (e.g. for frequencies substantially less than, substantially greater than, or otherwise substantially different than one or more resonance frequencies of the complementary metamaterial elements). For example, embodiments may deploy the Babinet complements of broadband metamaterial elements such as those described in R. Liu et al, "Broadband gradient index optics based on non-resonant metamaterials," unpublished; see attached Appendix) and/or in R. Liu et al, "Broadband ground-plane cloak," Science 323, 366 (2009)).

[0047] While the preceding exemplary embodiments are planar embodiments that are substantially two-dimensional, other embodiments may deploy complementary metamaterial elements in substantially non-planar configurations, and/or in substantially three-dimensional configurations. For example, embodiments may provide a substantially three-dimensional stack of layers, each layer having a conducting surface with embedded complementary metamaterial elements. Alternatively or additionally, the complementary metamaterial elements may be embedded in conducting surfaces that are substantially non-planar (e.g. cylinders, spheres, etc.). For example, an apparatus may include a curved conducting surface

(or a plurality thereof) that embeds complementary metamaterial elements, and the curved conducting surface may have a radius of curvature that is substantially larger than a typical length scale of the complementary metamaterial elements but comparable to or substantially smaller than a wavelength corresponding to an
5 operating frequency of the apparatus.

[0048] While the technology herein has been described in connection with exemplary illustrative non-limiting implementations, the invention is not to be limited by the disclosure. The invention is intended to be defined by the claims and to cover all corresponding and equivalent arrangements whether or not specifically disclosed
10 herein.

[0049] All documents and other information sources cited above are hereby incorporated in their entirety by reference.

WE CLAIM

1. An apparatus, comprising:
a conducting surface having a plurality of individual electromagnetic responses corresponding to respective apertures within the conducting surface, the plurality of individual electromagnetic responses providing an effective permeability in a direction parallel to the conducting surface.
2. The apparatus of claim 1, wherein the effective permeability is substantially zero.
3. The apparatus of claim 1, wherein the effective permeability is substantially less than zero.
4. The apparatus of claim 1, wherein the effective permeability in the direction parallel to the conducting surface is a first effective permeability in a first direction parallel to the conducting surface, and the plurality of respective individual electromagnetic responses further provides a second effective permeability in a second direction parallel to the conducting surface and perpendicular to the first direction.
5. The apparatus of claim 4, wherein the first effective permeability is substantially equal to the second effective permeability.
6. The apparatus of claim 4, wherein the first effective permeability is substantially different than the second effective permeability.
7. The apparatus of claim 6, wherein the first effective permeability is greater than zero, and the second effective permeability is less than zero.
8. The apparatus of claim 1, wherein the conducting surface is a bounding surface of a waveguide structure, and the effective permeability is an effective permeability for electromagnetic waves that propagate substantially within the waveguide structure.
9. An apparatus, comprising:
one or more conducting surfaces having a plurality of individual electromagnetic responses corresponding to respective apertures within the one or more conducting surfaces, the plurality of individual electromagnetic responses providing an effective refractive index that is substantially less than or equal to zero.

10. An apparatus, comprising:

one or more conducting surfaces having a plurality of individual electromagnetic responses corresponding to respective apertures within the one or more conducting surfaces, the plurality of individual electromagnetic responses providing a spatially-varying effective refractive index.

11. The apparatus of claim 10, wherein the one or more conducting surfaces are one or more bounding surfaces of a waveguide structure, and the spatially-varying effective refractive index is a spatially-varying effective refractive index for electromagnetic waves that propagate substantially within the waveguide structure.

12. The apparatus of claim 11, wherein the waveguide structure is a substantially planar two-dimensional waveguide structure.

13. The apparatus of claim 11, wherein the waveguide structure defines an input port for receiving input electromagnetic energy.

14. The apparatus of claim 13, wherein the input port defines an input port impedance for substantial nonreflection of input electromagnetic energy.

15. The apparatus of claim 14, wherein the plurality of respective individual electromagnetic responses further provides an effective wave impedance that gradiently approaches the input port impedance at the input port.

16. The apparatus of claim 13, wherein the waveguide structure defines an output port for transmitting output electromagnetic energy.

17. The apparatus of claim 16, wherein the output port defines an output port impedance for substantial nonreflection of output electromagnetic energy.

18. The apparatus of claim 16, wherein the plurality of respective individual electromagnetic responses further provides an effective wave impedance that gradiently approaches the output port impedance at the output port.

19. The apparatus of claim 16, wherein the waveguide structure is responsive to a substantially collimated beam of input electromagnetic energy defining an input beam direction to provide a substantially collimated beam of output electromagnetic energy defining an output beam direction substantially different than the input beam direction.

20. The apparatus of claim 19, wherein the waveguide structure defines an axial direction directed from the input port to the output port, and the spatially-varying effective refractive index includes, intermediate the input port and the output port, a substantially linear gradient along a direction perpendicular to the axial direction.

21. The apparatus of claim 16, wherein the waveguide structure is responsive to a substantially collimated beam of input electromagnetic energy to provide a substantially converging beam of output electromagnetic energy.

22. The apparatus of claim 21, wherein the waveguide structure defines an axial direction directed from the input port to the output port, and the spatially-varying effective refractive index includes, intermediate the input port and the output port, a substantially concave variation along a direction perpendicular to the axial direction.

23. The apparatus of claim 16, wherein the waveguide structure is responsive to a substantially collimated beam of input electromagnetic energy to provide a substantially diverging beam of output electromagnetic energy.

24. The apparatus of claim 23, wherein the waveguide structure defines an axial direction directed from the input port to the output port, and the spatially-varying effective refractive index includes, intermediate the input port and the output port, a substantially convex variation along a direction perpendicular to the axial direction.

25. The apparatus of claim 16, further comprising:
one or more patch antennas coupled to the output port.

26. The apparatus of claim 25, further comprising:
one or more electromagnetic emitters coupled to the input port.

27. The apparatus of claim 16, further comprising:
one or more electromagnetic receivers coupled to the input port.

28. An apparatus, comprising:
one or more conducting surfaces having a plurality of adjustable individual electromagnetic responses corresponding to respective apertures within the one or more conducting surfaces, the plurality of adjustable individual electromagnetic responses providing one or more adjustable effective medium parameters.

29. The apparatus of claim 26, wherein the one or more adjustable effective medium parameters includes an adjustable effective permittivity.

30. The apparatus of claim 26, wherein the one or more adjustable effective medium parameters includes an adjustable effective permeability.

31. The apparatus of claim 26, wherein the one or more adjustable effective medium parameters includes an adjustable effective refractive index.

32. The apparatus of claim 26, wherein the one or more adjustable effective medium parameters includes an adjustable effective wave impedance.

33. The apparatus of claim 26, wherein the adjustable individual electromagnetic responses are adjustable by one or more external inputs.

34. The apparatus of claim 31, wherein the one or more external inputs includes one or more voltage inputs.

35. The apparatus of claim 31, wherein the one or more external inputs includes one or more optical inputs

36. The apparatus of claim 31, wherein the one or more external inputs includes an external magnetic field

37. A method, comprising:
selecting a pattern of electromagnetic medium parameters; and
determining respective physical parameters for a plurality of apertures positionable in one or more conducting surfaces to provide a pattern of effective electromagnetic medium parameters that substantially corresponds to the selected pattern of electromagnetic medium parameters.

38. The method of claim 37, further comprising:

milling the plurality of apertures in the one or more conducting surfaces.

39. The method of claim 37, wherein the determining respective physical parameters includes determining according to one of a regression analysis and a lookup table.

40. A method, comprising:

selecting an electromagnetic function; and

determining respective physical parameters for a plurality of apertures positionable in one or more conducting surfaces to provide the electromagnetic function as an effective medium response.

41. The method of claim 40, wherein the electromagnetic function is a waveguide beam-steering function.

42. The method of claim 41, wherein the waveguide beam-steering function defines a beam deflection angle, and the selecting of the waveguide beam-steering function includes a selecting of the beam deflection angle.

43. The method of claim 40, wherein the electromagnetic function is a waveguide beam-focusing function.

44. The method of claim 43, wherein the waveguide beam-focusing function defines a focal length, and the selecting of the waveguide beam-focusing function includes a selecting of the focal length.

45. The method of claim 40, wherein the electromagnetic function is an antenna array phase-shifting function.

46. The method of claim 40, wherein the determining respective physical parameters includes determining according to one of a regression analysis and a lookup table.

47. A method, comprising:
selecting a pattern of electromagnetic medium parameters; and
for one or more conducting surfaces having a plurality of apertures with respective adjustable physical parameters, determining respective values of the respective adjustable physical parameters to provide a pattern of effective electromagnetic medium parameters that substantially corresponds to the selected pattern of electromagnetic medium parameters.

48. The method of claim 47, wherein the respective adjustable physical parameters are functions of one or more control inputs, and the method includes:
providing the one or more control inputs corresponding to the determined respective values of the respective adjustable physical parameters.

49. The method of claim 47, wherein the determining includes determining according to one of a regression analysis and a lookup table.

50. A method, comprising:
selecting an electromagnetic function; and
for one or more conducting surfaces having a plurality of apertures with respective adjustable physical parameters, determining respective values of the respective adjustable physical parameters to provide the electromagnetic function as an effective medium response.

51. The method of claim 50, wherein the respective adjustable physical parameters are functions of one or more control inputs, and the method includes:
providing the one or more control inputs corresponding to the determined respective values of the respective adjustable physical parameters.

52. The method of claim 50, wherein the determining includes determining according to one of a regression analysis and a lookup table.

53. A method, comprising:
delivering electromagnetic energy to an input port of a waveguide structure to produce an effective medium response within the waveguide structure, where the

effective medium response is a function of a pattern of apertures in one or more bounding conductors of the waveguide structure.