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(54) **METHOD AND APPARATUS FOR ELECTROMAGNETIC RESONANCE USING NEGATIVE INDEX MATERIAL**

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G02F 1/295	(2006.01)
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G02B 6/26	(2006.01)
G02B 6/42	(2006.01)

(52) **U.S. Cl.** **385/129**; 385/2; 385/9; 385/31

(58) **Field of Classification Search** 385/129, 385/1, 2, 4, 8, 9, 31

See application file for complete search history.

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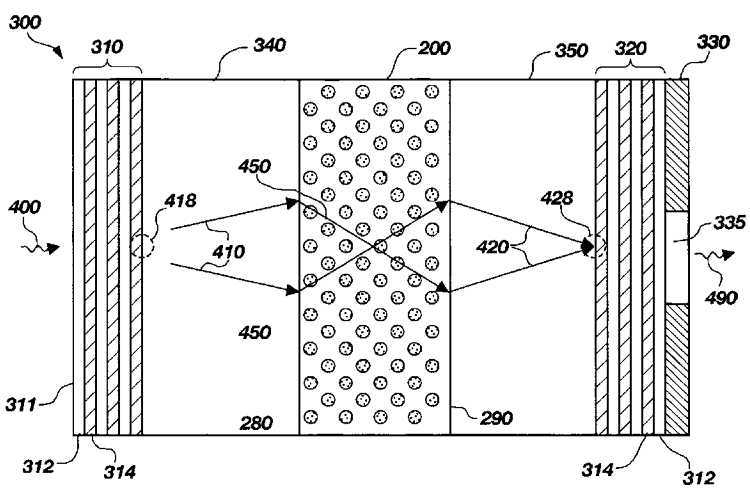
Assistant Examiner — Jerry Blevins

(57) **ABSTRACT**

An electromagnetic resonance device includes an input reflector, an output reflector, and a periodic dielectric medium (PDM) disposed between the input reflector and the output reflector. The input reflector and output reflector are configured to be reflective to radiation having a wavelength of interest. The PDM includes a periodic structure having a dielectric periodicity between a first surface and a second surface. The dielectric periodicity is configured with a negative refraction for the wavelength of interest. A first radiation is reflected by the input reflector toward the first surface of the PDM, passes through the PDM, and is focused on the output reflector as a second radiation. The second radiation is reflected by the output reflector toward the second surface of the PDM, passes through the PDM, and is focused on the input reflector as the first radiation.

25 Claims, 3 Drawing Sheets



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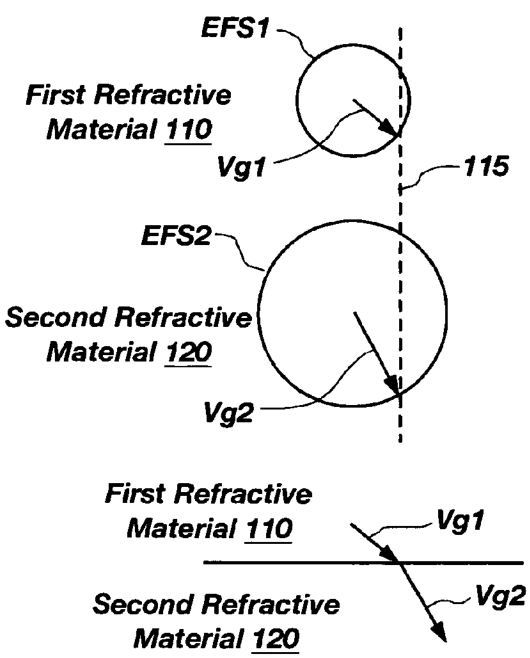


FIG. 1A

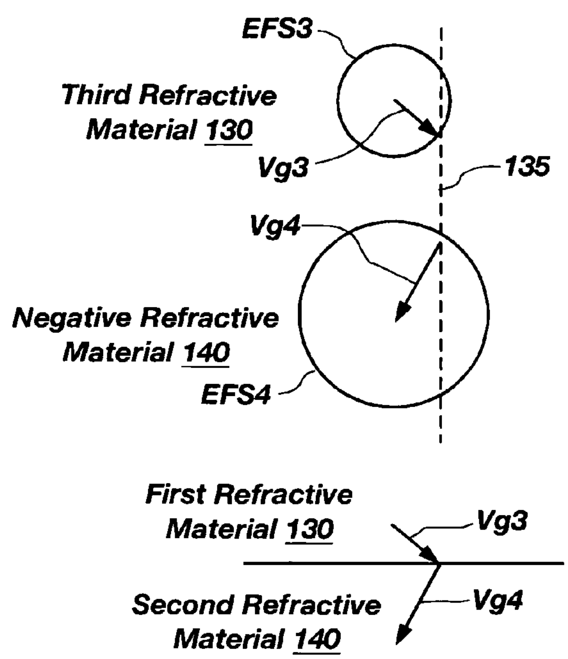


FIG. 1B

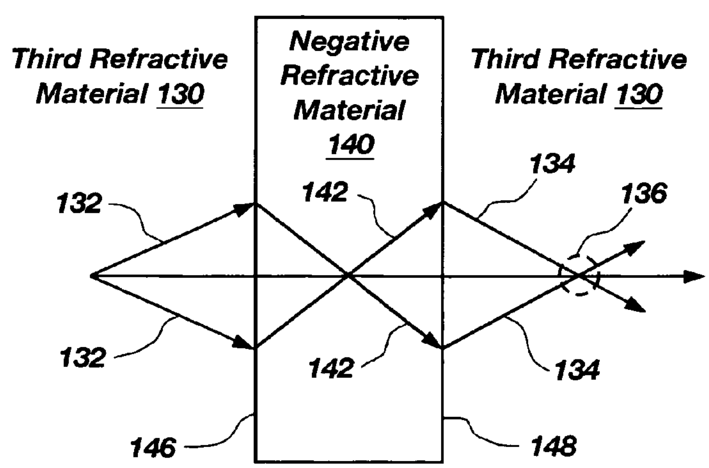


FIG. 2

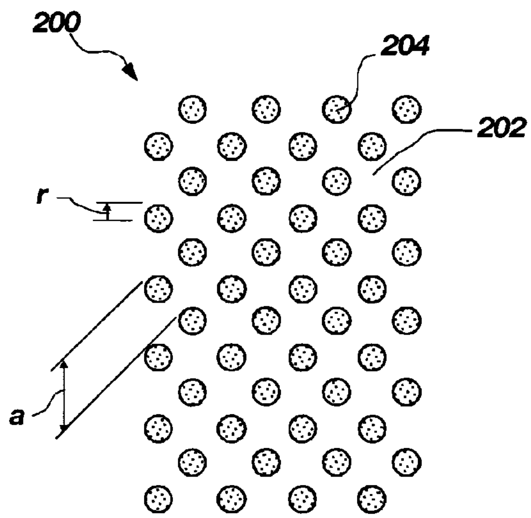


FIG. 3A

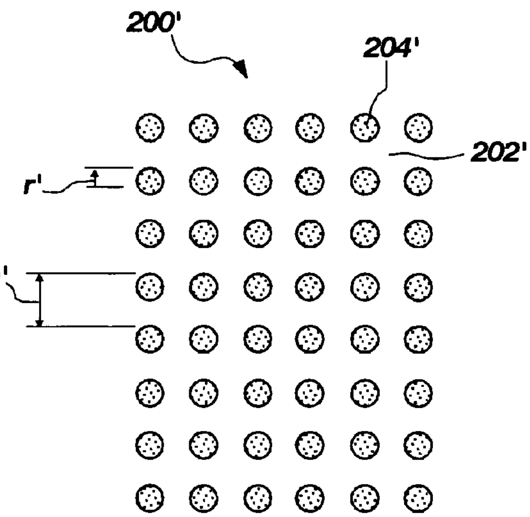


FIG. 3B

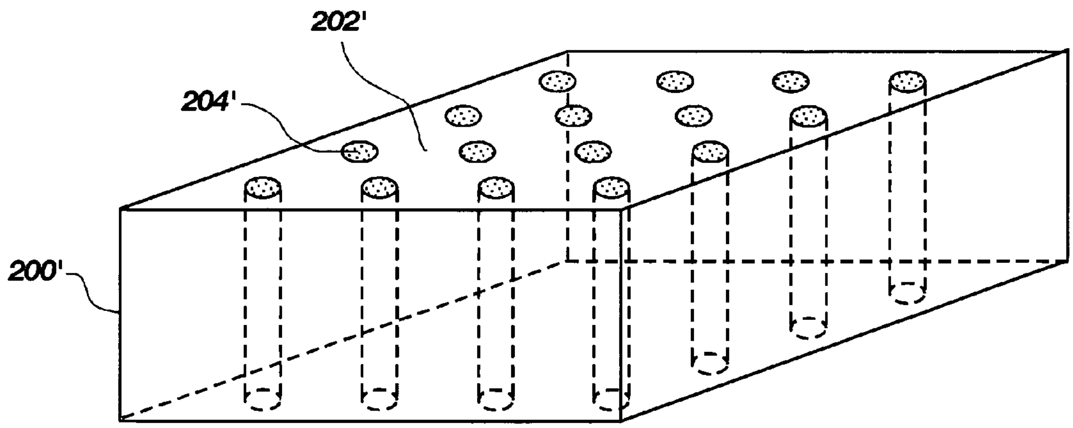


FIG. 4

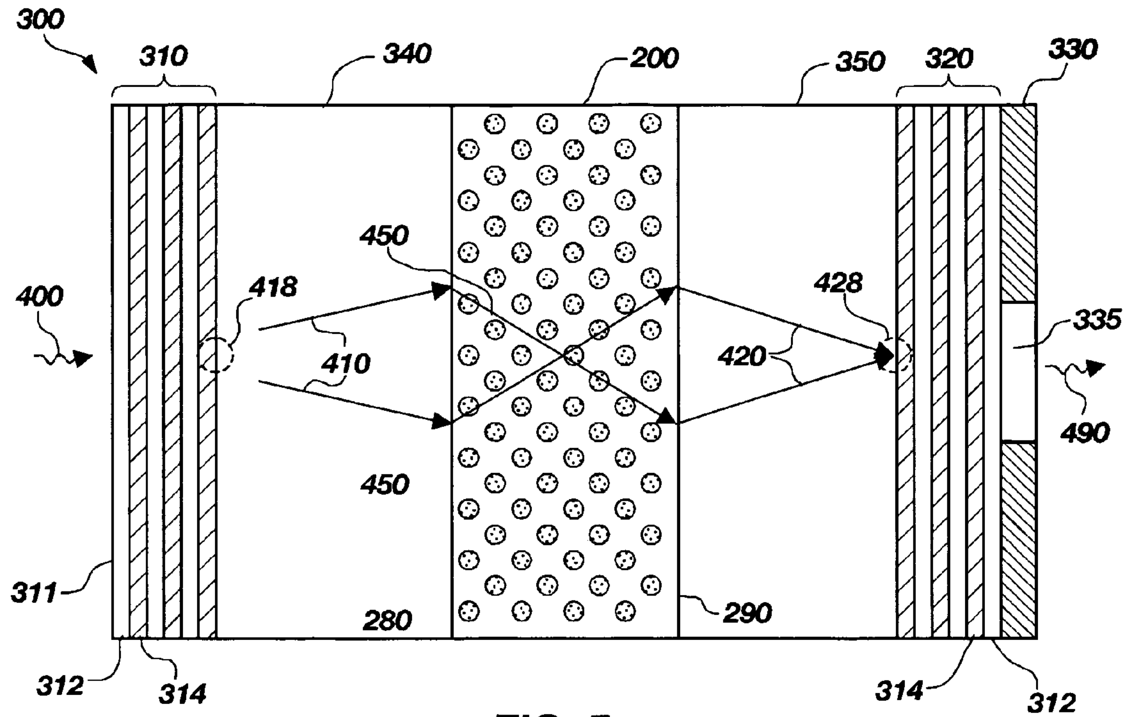
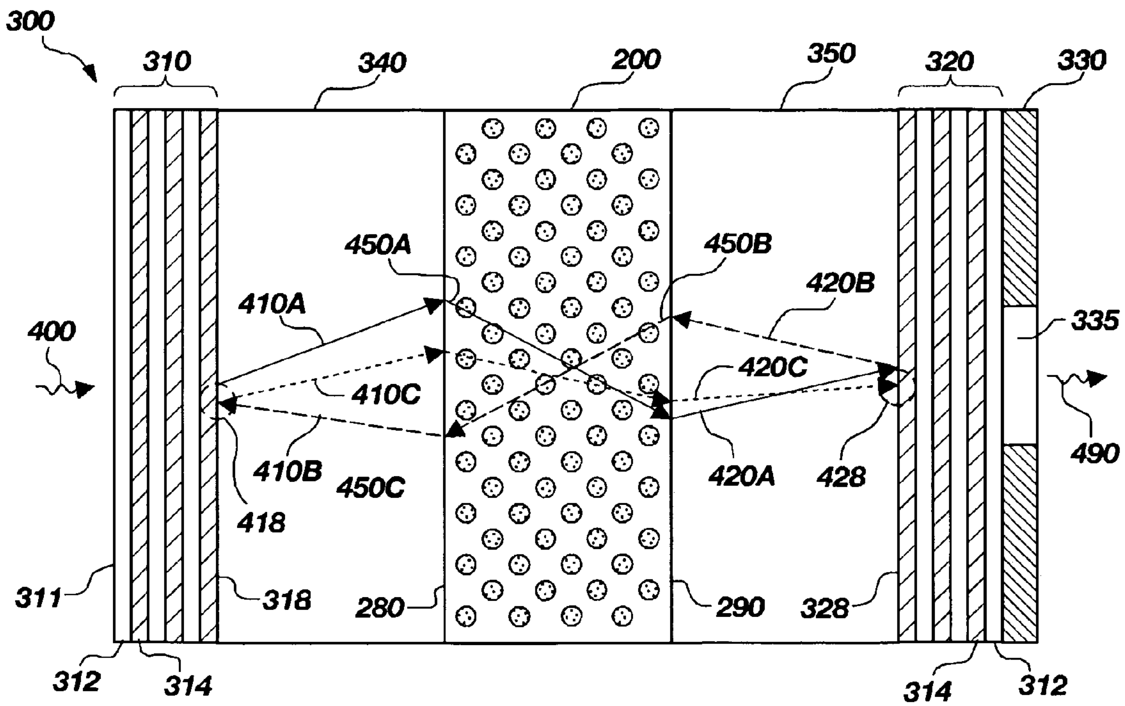

300
310
340
200
350
320
330
450
418
428
400
410
420
335
490
450
311
280
290
312
314
314
312

FIG. 5


300
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340
200
350
320
330
450A
450B
410A
420B
400
335
420C
410C
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420A
428
490
418
311
318
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290
328
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314
312

FIG. 6

METHOD AND APPARATUS FOR ELECTROMAGNETIC RESONANCE USING NEGATIVE INDEX MATERIAL

FIELD OF THE INVENTION

The present invention relates generally to modifying an electromagnetic radiation beam and more particularly to devices with a negative refractive index and structures for generating electromagnetic resonance using negative refraction.

BACKGROUND OF THE INVENTION

Photonic crystals are a class of man-made materials, which are often referred to as "meta-materials." Photonic crystals are formed by dispersing a material of one dielectric constant periodically within a matrix having a different dielectric constant. A one-dimensional photonic crystal is a three-dimensional structure that exhibits periodicity in dielectric constant in only one dimension. Bragg mirrors are an example of a one-dimensional photonic crystal. The alternating thin layers have different dielectric constants and refractive indices. The combination of several thin layers forms a three-dimensional structure that exhibits periodicity in dielectric constant in only the direction orthogonal to the planes of the thin layers. No periodicity is exhibited in either of the two dimensions contained within the plane of the layers.

A two-dimensional (2D) photonic crystal can be formed by periodically dispersing rods or columns of a material of one dielectric constant within a matrix having a different dielectric constant. 2D photonic crystals exhibit periodicity in two dimensions (i.e., the directions perpendicular to the length of the rods or columns) but no periodicity is exhibited in the direction parallel to the length of the columns.

Finally, a three-dimensional photonic crystal can be formed by periodically dispersing small spheres or other spatially confined areas of a first material having a first dielectric constant within a matrix of a second material having a second, different, dielectric constant. Three-dimensional photonic crystals exhibit periodicity in dielectric constant in all three dimensions within the crystal.

Photonic crystals may exhibit a photonic bandgap over a range of frequencies in directions exhibiting periodicity in dielectric constant. In other words, there may be a range of frequencies of electromagnetic radiation that will not be transmitted through the photonic crystal in the directions exhibiting dielectric periodicity. This range of frequencies that are not transmitted is known as a photonic bandgap of the photonic crystal.

For an introduction to photonic crystals and their uses and applications, the reader is referred to John D. Joannopoulos, Robert D. Meade & Joshua N. Winn, *Photonic Crystals—Molding the Flow of Light,* (Princeton University Press 1995) and K. Inoue & K. Ithaca, *Photonic Crystals—Physics, Fabrication and Applications,* (Springer 2004)

In natural materials, electromagnetic radiation is refracted at a specific angle and in a specific direction when it encounters a junction between two materials. A class of meta-materials has been studied that refract electromagnetic radiation in the opposite direction from the direction of natural materials. These materials exhibiting negative refraction are often called super-lenses for their ability to refract in a negative direction and, as a result, refocus the electromagnetic radiation, rather than causing the electromagnetic radiation to disperse. Recently, it has been shown that photonic crystals may exhibit this negative refractive index. Many new and useful applications may be possible for these super-lens structures, particularly photonic crystals exhibiting negative refraction.

BRIEF SUMMARY OF THE INVENTION

The present invention, in a number of embodiments, includes methods of developing resonance in an electromagnetic radiation beam and photonic crystals exhibiting negative super-lens properties, wherein the negative refraction properties of the photonic crystals may be used to create resonant structures.

An embodiment of the present invention includes an electromagnetic resonance device comprising an input reflector, an output reflector, and a periodic dielectric medium disposed between the input reflector and the output reflector. The input reflector is configured to be substantially reflective to a first radiation having a wavelength of interest. The output reflector is disposed in a plane substantially parallel to the input reflector and is configured be substantially reflective to a second radiation having the wavelength of interest. The periodic dielectric medium is disposed between the: input reflector and the output reflector and includes a first surface and a second surface, which are each in a plane substantially parallel to the input reflector. In addition, the periodic dielectric medium includes a periodic structure having a dielectric periodicity between the first surface and the second surface. The periodic structure is configured with a negative refraction for electromagnetic radiation at the wavelength of interest. The negative refraction of the periodic dielectric medium focuses the first radiation impinging on the first surface as the second radiation at a second focal location. Similarly, the negative refraction of the periodic dielectric medium focuses the second radiation impinging on the second surface as the first radiation at a first focal location.

Another embodiment of the present invention comprises a method of intensifying an electromagnetic radiation beam. The method includes providing a periodic dielectric medium comprising a negative refractive index at a wavelength of interest. The method further includes reflecting a first radiation toward a first surface of the periodic dielectric medium and reflecting a second radiation toward a second surface of the periodic dielectric medium. The method further includes focusing the second radiation at a second focal location by the first radiation passing through the periodic dielectric medium from the first surface to the second surface. Similarly, the method further includes focusing the first radiation at a first focal location by the second radiation passing through the periodic dielectric medium from the second surface to the first surface.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

While the specification concludes with claims particularly pointing out and distinctly claiming that which is regarded as the present invention, the advantages of this invention can be more readily ascertained from the following description of the invention when read in conjunction with the accompanying drawings in which:

FIG. **1**A is a wave-vector diagram illustrating directions of wave propagation at an interface between two isotropic materials;

FIG. **1**B is a wave-vector diagram illustrating directions of wave propagation at an interface between an isotropic material and a material exhibiting a negative refractive index;

FIG. **2** illustrates focusing properties of electromagnetic radiation traveling through materials exhibiting a negative refractive index;

FIG. **3**A illustrates a top view of a representative periodic dielectric medium comprising a 2D photonic crystal configured with a triangular lattice;

FIG. **3**B illustrates a top view of a representative periodic dielectric medium comprising a 2D photonic crystal configured with a square lattice;

FIG. **4** is a three-dimensional view of a representative 2D photonic crystal configured with a square lattice;

FIG. **5** is a top view of a representative electromagnetic radiation resonant structure including a 2D photonic crystal illustrating a negative refraction that focuses electromagnetic radiation; and

FIG. **6** is a top view of a representative electromagnetic radiation resonant structure including a 2D photonic crystal illustrating a negative refraction and resonance.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, micron-scale dimensions refer roughly to dimensions that range from one micrometer up to a few micrometers, sub-micron scale dimensions refer roughly to dimensions that range from 1 micrometer down to 0.05 micrometers, and nanometer scale dimensions refer roughly to dimensions that range from 1 nanometer up to 50 nanometers (0.05 micrometers).

The present invention, in a number of embodiments, includes electromagnetic radiation resonant structures and methods of developing resonance in an electromagnetic radiation beam. Embodiments of the present invention are configured for providing a periodic dielectric medium that includes a negative refractive index for radiation having a selected wavelength range. For radiation directed at a resonant structure (including the periodic dielectric medium) negative refraction of the radiation as it passes through the periodic dielectric medium (PDM) may generate a focused radiation and a resonance within the resonant structure.

With regard to refraction, Snell's law is a well-known law that models refraction characteristics of a radiation beam as the radiation beam encounters an interface between two mediums with different refractive properties. Basically, Snell's law states that the product of the refractive index and the sine of the angle of incidence of a radiation beam in one medium is equal to the product of the refractive index and the sine of the angle of refraction in a successive medium.

Generally, naturally occurring materials exhibit a positive refractive index. In other words, a radiation beam with an oblique incident angle to a facet of a medium with a high positive refractive index may be deviated toward the surface normal of the facet, and a radiation beam entering a medium of lower refractive index may be deviated away from the surface normal, but the deviation occurs at a positive angle relative to the surface normal. Recently, a number of man-made materials (often referred to as meta-materials) have been developed that exhibit a negative refractive index. With a negative refractive index, the material still obeys Snell's law, but the radiation beam is deviated in the opposite direction from natural materials (i.e., with a negative angle relative to the surface normal). Thus, using Snell's law, the product of the refractive index and the sine of the angle of incidence of a radiation beam in one medium is equal to the negative of the product of the refractive index and the sine of the angle of refraction in a successive medium.

The refractive properties of a positive refractive index and a negative refractive index may be understood using FIGS. **1**A, **1**B, and **2**. FIG. **1**A is a wave-vector diagram illustrating directions of wave propagation through two refractive materials (**110** and **120**) and at the interface between the two refractive materials (**110** and **120**). Similarly, FIG. **1**B is a wave-vector diagram illustrating directions of wave propagation at an interface between a third refractive material **130** and a negative refractive material **140**.

FIG. **1**A illustrates positive refraction. In FIG. **1**A the upper circle illustrates an equal frequency surface EFS**1** plot of a first refractive material **110**. The lower circle illustrates an equal frequency surface EFS**2** plot of a second refractive material **120**. EFS**2** is a different diameter than EFS**1** due, in part, to the difference in dielectric properties between the first refractive material **110** and the second refractive material **120**. Group velocity vector Vg**1** is oriented perpendicular to, and away from the center of, EFS**1** and illustrates the direction of wave propagation through the first refractive material **110**. A first frequency line **115** illustrates a specific frequency at which group velocity vector Vg**1** intersects EFS**1**. The first frequency line **115** is carried down to intersect with EFS**2**. Thus, a group velocity vector Vg**2**, oriented perpendicular to and away from the center of EFS**2**, defines the direction of wave propagation through the second refractive material **120** at the same frequency as the wave propagating through the first refractive material **110**. The lower portion of FIG. **1**A illustrates the two group velocity vectors Vg**1** and Vg**2** and the direction change that occurs at the boundary between the first refractive medium **110** and the second refractive medium **120**. The direction change is due to the difference in the refractive index of the two refractive materials (**110** and **120**). The positive refraction can be seen by the positive angle from the surface normal for group velocity vector Vg**2**.

FIG. **1**B illustrates negative refraction. In FIG. **1**B the upper circle illustrates an equal frequency surface EFS**3** plot of a third refractive material **130**. The lower circle illustrates an equal frequency surface EFS**4** plot of a negative refractive material **140**. EFS**4** is a different diameter than EFS**3** due, in part, to the difference in dielectric properties between the first refractive material **110** and the negative refractive material **140**. In addition, in negative refractive index material **140**, as the frequency increases the equal frequency surface EFS**4** moves inward around the symmetry point. Therefore, the group velocity vector Vg**4** points inward indicating negative refraction. As a result, group velocity vector Vg**4**, illustrating the direction of wave propagation through the negative refractive material **140**, is oriented perpendicular to, but toward from the center of, EFS**4**.

On the other hand, the third refractive material **130** is a positive refractive material similar to the first refractive material **110** and the second refractive material **120**. Therefore, group velocity vector Vg**3** is oriented perpendicular to and away from the center of EFS**3**, and illustrates the direction of wave propagation through the third refractive material **130**. A second frequency line **135** illustrates a specific frequency at which group velocity vector Vg**3** intersects EFS**3**. The second frequency line **135** is carried down to intersect with EFS**4**. Thus, group velocity vector Vg**4** defines the direction of wave propagation through the negative refractive material **140** of a wave at the same frequency as the wave propagating through the third refractive material **130**. The lower portion of FIG. **1**B illustrates the two group velocity vectors Vg**3** and Vg**4** and the direction change that occurs at the boundary between the third refractive medium **130** and the negative refractive medium **140**. The negative refraction can be seen by the negative angle from the surface normal for group velocity vector Vg**4**.

FIG. 2 illustrates focusing properties of electromagnetic radiation traveling through a material exhibiting a negative refractive index. In FIG. 2, a top view illustrates a slab of negative refractive material 140, with third refractive material 130 on opposite sides of the negative refractive material 140. Incident electromagnetic radiation beams have first directions 132 when they impinge on an incident surface 146 of the negative refractive material 140. The negative refractive property of negative refractive material 140 cause the electromagnetic radiation beams to deviate towards second directions 142 with a negative angle from the surface normal of the incident surface 146. As the electromagnetic radiation beams emit from an emitting surface 148 of the negative refractive material 140, they deviate towards third directions 134. As the electromagnetic radiation beams travel in the third direction 134, they converge at a focal point 136.

Photonic crystals have been shown to posses this negative refractive property for certain proportions of the geometry of the photonic crystal relative to the wavelength of electromagnetic radiation that will experience the negative refraction. Some embodiments of photonic crystals are shown in FIGS. 3A, 3B, and 4.

FIG. 3A illustrates a top view of a periodic dielectric medium 200 comprising a 2D photonic crystal 200 configured with a triangular lattice (also referred to as a hexagonal lattice). The 2D photonic crystal 200 comprises a matrix 202 (also referred to as a first material 202). Within the matrix 202, periodically spaced columns 204 (also referred to as cylindrical regions, rods, or a second material) are disposed in an array of horizontal rows and vertical rows. As illustrated in FIG. 3A, these horizontal rows and vertical rows of rods 204 may be disposed to form a triangular lattice wherein each alternate horizontal row and vertical row is displace about half way between the adjacent horizontal row and vertical row.

FIG. 3B illustrates a top view of a periodic dielectric medium 200' comprising a 2D photonic crystal 200' configured with a square lattice, wherein the periodically spaced columns 204' in adjacent horizontal rows and vertical rows are orthogonally aligned within the matrix 202'. FIG. 4 shows a three-dimensional view of the 2D photonic crystal 200' of FIG. 3A to illustrate the lengthwise dispersion of the rods 204' through the matrix 202'.

In a 2D photonic crystal 200, the matrix 202 comprises a first material 202 with a first dielectric constant and the rods 204 comprise a second material 204 with a second dielectric constant. Thus, dielectric periodicity is exhibited in the photonic crystal in directions perpendicular to the longitudinal axis of the rods 204. If the difference in dielectric constant between the first material 202 and the second material 204 is large enough, a photonic bandgap (i.e., a forbidden frequency range) may occur. This photonic bandgap may create a variety of interesting properties for the photonic crystal. One of those properties is negative refraction.

By way of example and not limitation, a 2D photonic crystal 200 may comprise a matrix 202 of silicon with rods 204 of air, or a matrix 202 of air with rods 204 of silicon. In these embodiments, silicon has a dielectric constant of about 12 and air has a dielectric constant of about one. Other materials, such as, for example, InP, GaAs, and GaInAsP, have been shown to posses a photonic bandgap in combinations with each other and with air. Materials may be chosen to optimize a variety of parameters such as wavelengths where the photonic bandgap occurs, ease of manufacturing, negative refractive properties, or combinations thereof.

Referring to FIGS. 3A and 3B, the photonic crystals have a lattice constant (a, a'), which indicates the lateral spacing between the centers of adjacent rods 204, and the rods 204 have a substantially uniform radius (r, r'). For many purposes, it is useful to discuss a relative radius (i.e. RR=r/a) or discuss the radius (r) as a ratio of the lattice constant (a). By way of example and not limitation, a 2D photonic crystal 200 may be characterized with a lattice constant (a) and a radius proportional to the lattice constant (such as r=0.4a and r=0.35a).

Determining the photonic band structure of a particular photonic crystal is a complex problem that involves solving Maxwell's equations and considering the periodic variation in the dielectric constant through the photonic crystal. Thus, the photonic band structure is at least partially a function of the dielectric constant of the matrix 202, the dielectric constant of the rods 204, the radius (r) of the rods 204, and the lattice constant (a). Computational methods for computing the band structure of a particular photonic crystal are known in the art. An explanation of these computational methods may be found in John D. Giannopoulos, Robert D. Meade & Joshua N. Winn, Photonic Crystals—Molding the Flow of Light, (Princeton University Press 1995), in particular at Appendix D.

Simulations have shown that the negative refractive property of a photonic crystal will be present for a range of wavelengths (A) within a photonic bandgap of the photonic crystal. By way of example and not limitation, Qui et al. have presented simulations of a 2D photonic crystal 200 comprising InP—InGaAsP indicating a refractive index of about −0.73 with a ratio of lattice constant (a) to frequency (i.e., a/λ) of about 0.325 (IEEE Journal of Selected Topics in Quantum Electronics, Vol. 9, No. 1, January/February 2003, pp. 106-110). In other words, using this illustrative simulation, an infrared radiation beam with a wavelength of about 1230 nm may exhibit a refractive index of about −0.73 when passing through the 2D photonic crystal 200 with a lattice constant (a) of about 400 nm.

FIGS. 5 and 6 are top view illustrations of a representative electromagnetic resonance device 300 including a 2D photonic crystal 200 configured with a triangular lattice. The 2D photonic crystal 200 is positioned between an input reflector 310 and an output reflector 320.

The input reflector 310 and the output reflector 320 may be configured as Bragg reflectors. Bragg reflectors (also referred to as Bragg Mirrors) may be formed in a number of ways using a variety of materials configured as alternating layers having a low and a high refractive index. Each layer may be configured with a thickness of about a quarter wavelength of the wavelength of interest to be amplified by the electromagnetic resonance device 300. The resulting Bragg reflector may also be referred to as a quarter-wave stack. As an example, a Bragg reflector may be formed from alternating layers of GaAs (gallium arsenide) and AlGaAs (aluminum gallium arsenide). Another suitable material combination for forming Bragg reflectors is alternating layers formed respectively from silicon and silicon dioxide. Implementing a larger number of alternating pairs in a Bragg reflector results in a higher refractive index.

By way of example and not limitation, the input Bragg reflector 310 and the output Bragg reflector 320 may be formed from alternating first layers 312 and second layers 314. About twenty to twenty-five layers may result in a reflectivity of about 99.9%, whereas about thirty layers may create a reflectivity as high as 99.99%.

An opaque or highly reflective aperture layer 330 may optionally be formed on the output Bragg reflector 320 to create an aperture 335 configured with a desired size and shape for an emitting radiation 490, which may be emitted through the output reflector 320.

The input reflector **310** is separated from the periodic dielectric medium **200** by a first intermediate medium **340**. Similarly, the output reflector **320** is separated from the periodic dielectric medium **200** by a second intermediate medium **350**. The intermediate media (**340**, **350**) may be the same material or may be different materials, depending on the desired refractive properties. By way of example and not limitation, the intermediate media (**340**, **350**) may comprise air, silicon, or any other suitable material for transmission of the wavelength of interest.

The electromagnetic resonance device **300** is optically pumped by a pump radiation **400** substantially at the wavelength of interest and directed at an input surface **311** of the input reflector **310**. A small portion of the pump radiation **400** may be transmitted through the input reflector **310** and enter the first intermediate medium **340** as a first radiation **410**.

FIG. **5** illustrates the focal properties of the periodic dielectric medium **200** due to negative refraction. The first radiation **410** travels through the first intermediate medium **340** and impinges on a first surface **280** of the periodic dielectric medium **200**. The 2D photonic crystal **200** causes the first radiation **410** to deflect at a negative refraction angle at the interface between the first intermediate medium **340** and the 2D photonic crystal **200**. The radiation passes through the 2D photonic crystal **200** as refracted radiation **450**. When the refracted radiation **450** encounters the interface between the 2D photonic crystal **200** and the second intermediate medium **350**, it is deflected again at a negative refraction angle. The refracted radiation **450** enters the second intermediate medium **350** as a second radiation **420**. Overall, the negative refraction properties of the 2D photonic crystal **200** may cause the second radiation **420** to converge at a second focal location **428**.

The lines illustrating first radiation **410**, refracted radiation **450** and second radiation **420** are used to illustrate the approximate extent and direction of the radiation beams for ideal negative refraction. Those of ordinary skill in the art will recongnize that all possible angles for the first radiation **410** and second radiation **420**, along with corresponding refracted radiation **450** are implied by the drawings illustrating radiation beam refraction.

In addition, while not directly illustrated in FIG. **5**, it will be readily apparent to those of ordinary skill in the art that the radiation may travel in the opposite direction. In other words, radiation may travel from the output reflector **320** towards the input reflector **310** to focus the radiation at a first focal location **418**. This direction of travel is illustrated in FIG. **6**.

FIG. **6** illustrates the resonance properties of the electromagnetic resonance device **300** by following a hypothetical electromagnetic radiation beam. The first radiation **410**A travels through the first intermediate medium **340** and impinges on a first surface **280** of the periodic dielectric medium **200**. The 2D photonic crystal **200** causes the first radiation **410**A to deflect at a negative refraction angle at the interface between the first intermediate medium **340** and the 2D photonic crystal **200**. The radiation passes through the 2D photonic crystal **200** as refracted radiation **450**A. When the refracted radiation **450**A encounters the interface between the 2D photonic crystal **200** and the second intermediate medium **350**, it is deflected again at a negative refraction angle. The refracted radiation **450**A enters the second intermediate medium **350** as a second radiation **420**A.

The second radiation **420**A is reflected back toward the 2D photonic crystal **200** as second radiation **420**B. When second radiation **420**B encounters the interface between the second intermediate medium **350** and the 2D photonic crystal **200**, it is deflected again at a negative refraction angle to become refracted radiation **450**B. When the refracted radiation **450**B encounters the interface between the 2D photonic crystal **200** and the first intermediate medium **340**, it is deflected again at a negative refraction angle to become first radiation **410**B. First radiation **410**B is reflected back toward the 2D photonic crystal **200** as first radiation **410**C, which follows the same negative refraction process through the 2D photonic crystal to become refracted radiation **450**C and second radiation **420**C.

This resonance process of reflecting and focusing may continue indefinitely creating a high Q factor. The high Q factor may occur not only from the reflections, but also from the focusing and refocusing at the first focal location **418** and the second focal location **428**.

In addition, the Q factor may be increased by positioning the output mirror such that a second interior surface **328** of the output mirror is substantially near the second focal location **428**. Similarly, the Q factor may be increased by positioning the input mirror such that a first interior surface **318** of the input mirror is substantially near the first focal location **418**.

The output reflector **320** is not completely reflective. As a result, some of the radiation may be transmitted through the output reflector **320** as emitting radiation **490**.

Although this invention has been described with reference to particular embodiments, the invention is not limited to these described embodiments. Rather, the invention is limited only by the appended claims, which include within their scope all equivalent devices or methods that operate according to the principles of the invention as described.

What is claimed is:

1. An electromagnetic resonance device, comprising:

an input reflector substantially reflective to a first radiation having a wavelength of interest;

an output reflector in a plane substantially parallel to the input reflector and not completely reflective to a second radiation having the wavelength of interest;

a reflective aperture layer disposed on the output reflector and including an aperture; and

a periodic dielectric medium disposed between the input reflector and the output reflector, the periodic dielectric medium configured with a negative refraction at the wavelength of interest, wherein radiation having the wavelength of interest enters the resonance device through the input reflector, is reflected back and forth between the input reflector and the output reflector, and after each reflection is focused and refocused by the periodic dielectric medium on the input and output reflectors to intensify the radiation that is output as emitting radiation through the aperture.

2. The device of claim **1**, wherein the periodic dielectric medium comprises a 2D photonic crystal comprising a first material including a plurality of periodically spaced columns of a second material.

3. The device of claim **2**, wherein the first material comprises a dielectric material and the second material comprises air.

4. The device of claim **2**, wherein the first material comprises air and the second material comprises a dielectric material.

5. The device of claim **1**, wherein the input reflector comprises a Bragg reflector.

6. The device of claim **1**, wherein the output reflector comprises a Bragg reflector.

7. The device of claim **1**, wherein the first focal location is located at least substantially near the input reflector.

8. The device of claim **7**, wherein the second focal location is located at least substantially near the output reflector.

9. The device of claim **1**, wherein at least a portion of a pump radiation at the wavelength of interest is transmitted through the input reflector to enter the electromagnetic radiation device as the first radiation.

10. The device of claim **1**, wherein at least a portion of the second radiation is transmitted through the output reflector as the emitting radiation.

11. The device of claim **10**, wherein the aperture is configured to define a size and a shape of the emitting radiation.

12. A method of intensifying an electromagnetic radiation beam, comprising:

providing a periodic dielectric medium comprising a negative refractive index at a wavelength of interest;

reflecting a first radiation toward a first surface of the periodic dielectric medium;

reflecting a second radiation toward a second surface of the periodic dielectric medium;

focusing the second radiation at a second focal location by passing the first radiation through the periodic dielectric medium from the first surface to the second surface;

focusing the first radiation at a first focal location by passing the second radiation through the periodic dielectric medium from the second surface to the first surface; and

outputting intensified radiation through an aperture.

13. The method of claim **12**, wherein providing the periodic dielectric medium further comprises providing a 2D photonic crystal comprising a first material including a plurality of periodically spaced columns of a second material.

14. The method of claim **12**, wherein reflecting the first radiation comprises reflecting the first radiation with an input reflector.

15. The method of claim **14**, wherein focusing the first radiation further comprises locating the first focal location at least substantially near the input reflector.

16. The method of claim **14**, further comprising:

directing a pump radiation having the wavelength of interest at an exit surface of the input reflector; and

transmitting at least a portion of the pump radiation through the input reflector.

17. The method of claim **15**, wherein reflecting the second radiation comprises reflecting the first radiation with an output reflector.

18. The method of claim **17**, wherein focusing the second radiation further comprises locating the second focal location at least substantially near the output reflector.

19. The method of claim **17**, further comprising transmitting at least a portion of the second radiation through the output reflector.

20. The method of claim **12**, wherein reflecting the second radiation comprises reflecting the first radiation with an output reflector.

21. The method of claim **20**, wherein focusing the second radiation further comprises locating the second focal location substantially near an interior surface of the output reflector.

22. The method of claim **20**, further comprising transmitting at least a portion of the second radiation through the output reflector.

23. The method of claim **20**, wherein reflecting the first radiation comprises reflecting the first radiation with an input reflector.

24. The method of claim **23**, wherein focusing the first radiation further comprises locating the first focal location substantially near an interior surface of the input reflector.

25. The method of claim **23**, further comprising:

directing a pump radiation having the wavelength of interest at an exit surface of the input reflector; and

transmitting at least a portion of the pump radiation through the input reflector.

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