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(54) **LENS-FREE PLANAR IMAGER AND WIRELESS TRANSMITTER**

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(57) **ABSTRACT**

Techniques for lens-free imaging using optical resonance, including providing a series of standing waves indexed by a wave vector to an optical resonator having a predetermined dispersion relation. The intensity of the wavelengths corresponding to the standing waves can be measured with a photodetector. A magnitude and shift of the wave vector corresponding to each of the standing waves can be determined, and spatial information in k-space can be determined from the magnitude and shift of the wave vector corresponding to each of the standing waves using an inversion relationship. A transform can be applied to the spatial information to generate an image.

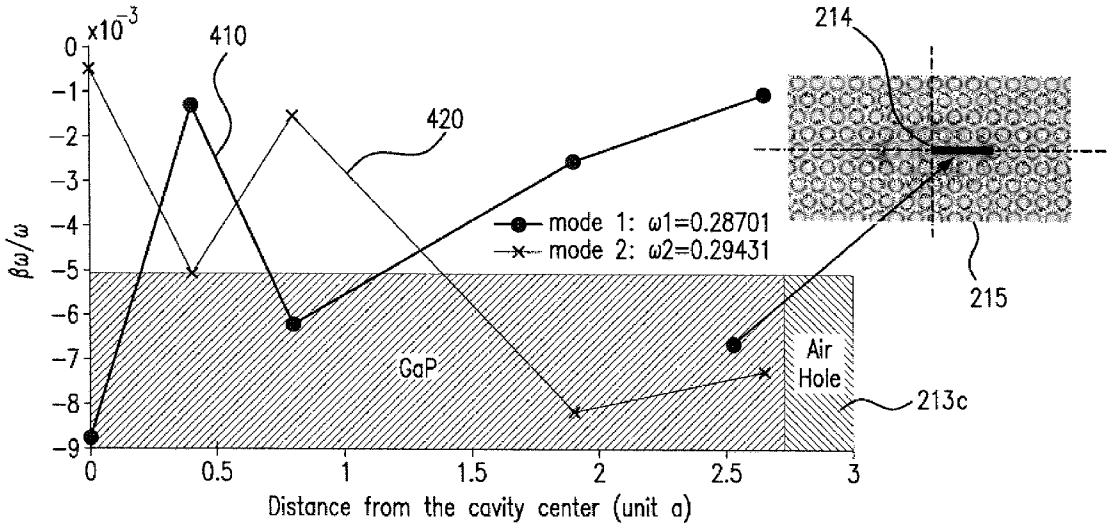


Fig. 1

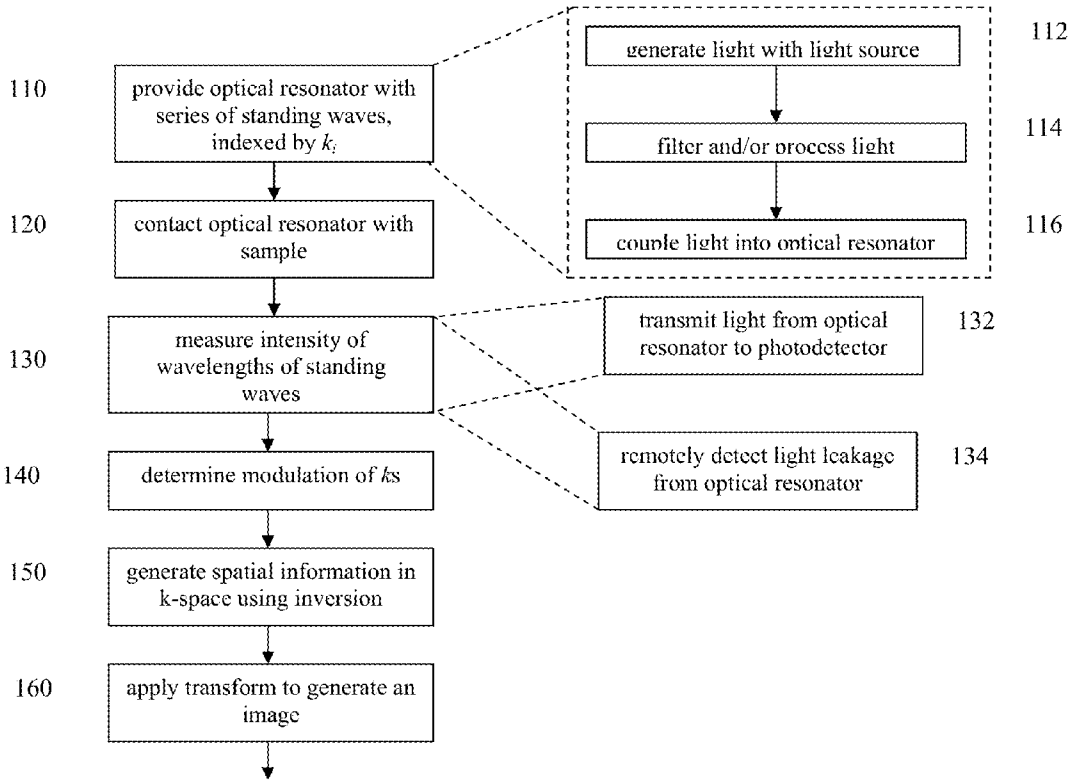

110
provide optical resonator with series of standing waves, indexed by k_i
120
contact optical resonator with sample
130
measure intensity of wavelengths of standing waves
140
determine modulation of ks
150
generate spatial information in k-space using inversion
160
apply transform to generate an image
112
generate light with light source
114
filter and/or process light
116
couple light into optical resonator
132
transmit light from optical resonator to photodetector
134
remotely detect light leakage from optical resonator

Fig. 2a

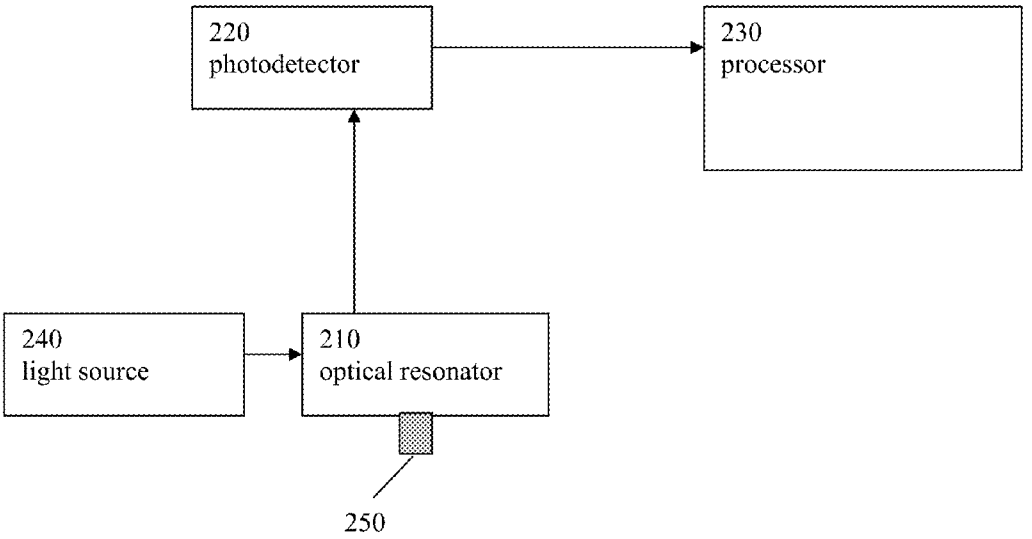

220
photodetector
230
processor
240
light source
210
optical resonator
250

Fig. 2b

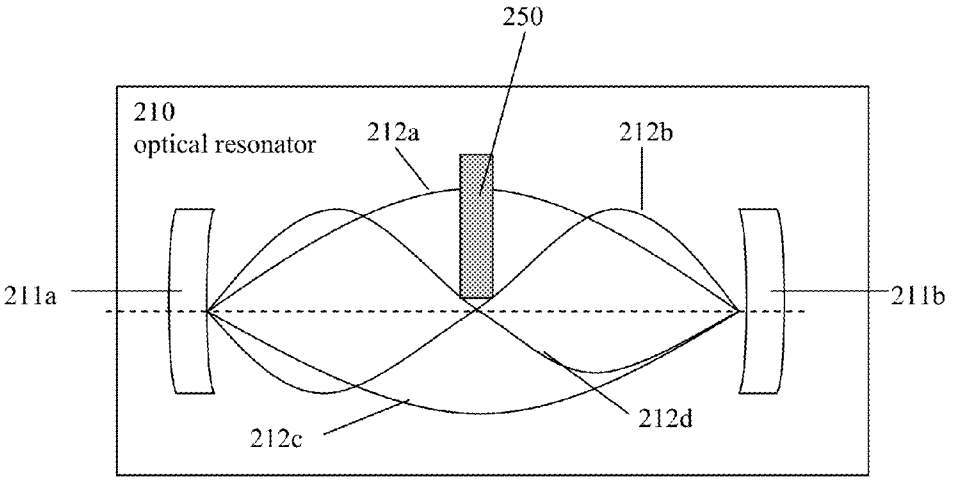

250
210
optical resonator
212a
212b
211a
211b
212c
212d

Fig. 2c

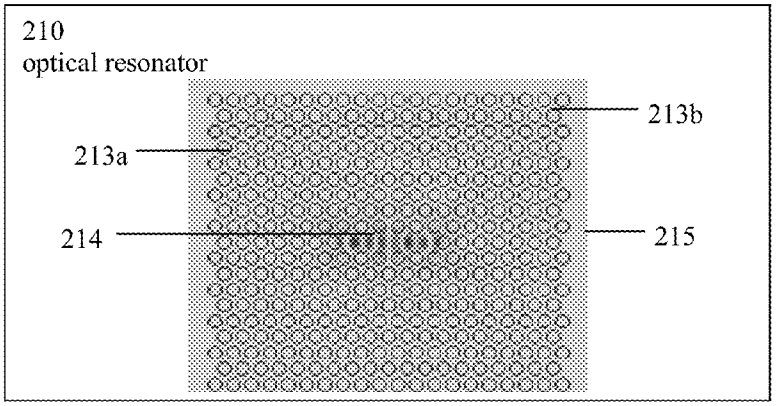
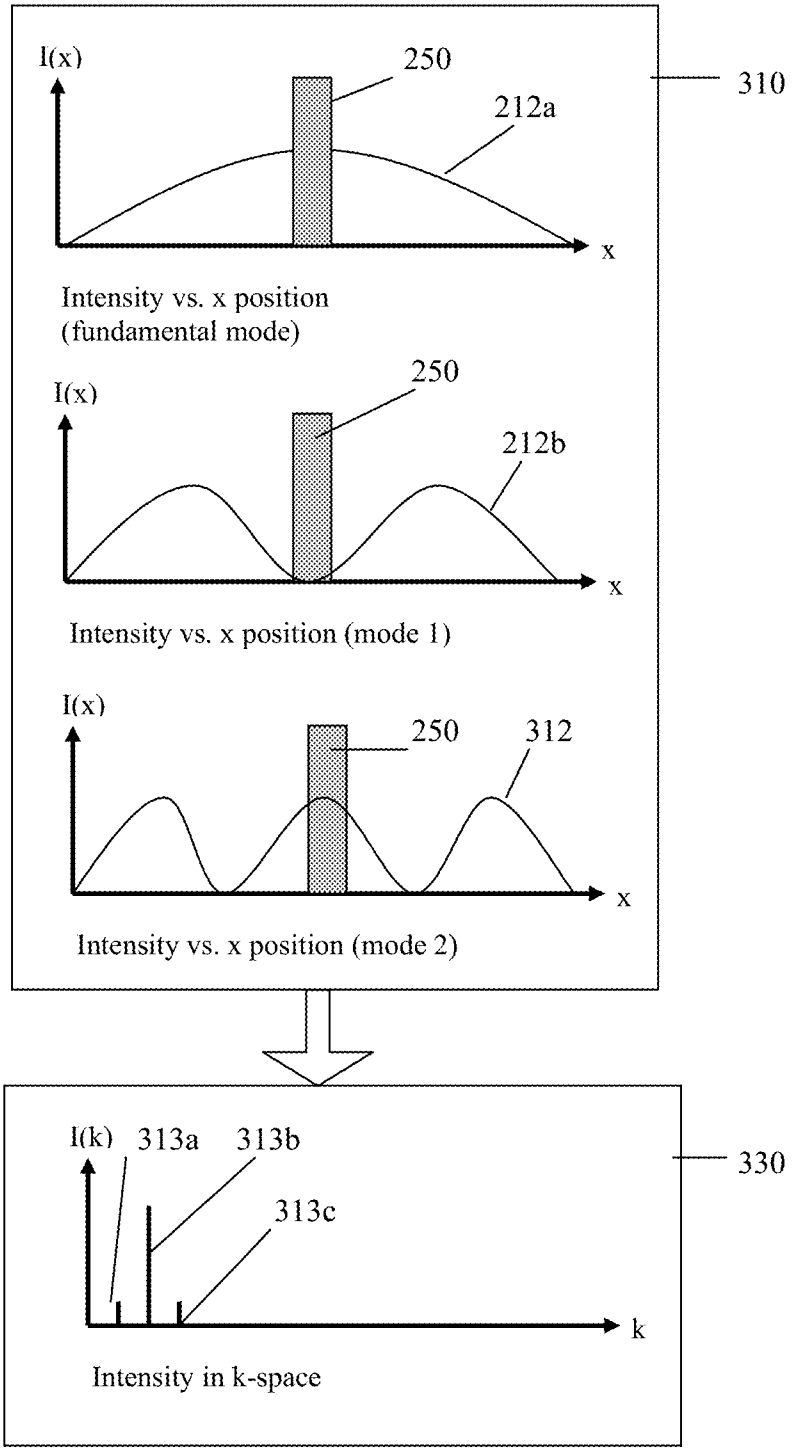


Fig. 3


I(x)
250
212a
310
x
Intensity vs. x position
(fundamental mode)
I(x)
250
212b
x
Intensity vs. x position (mode 1)
I(x)
250
312
x
Intensity vs. x position (mode 2)
I(k)
313a
313b
313c
330
k
Intensity in k-space

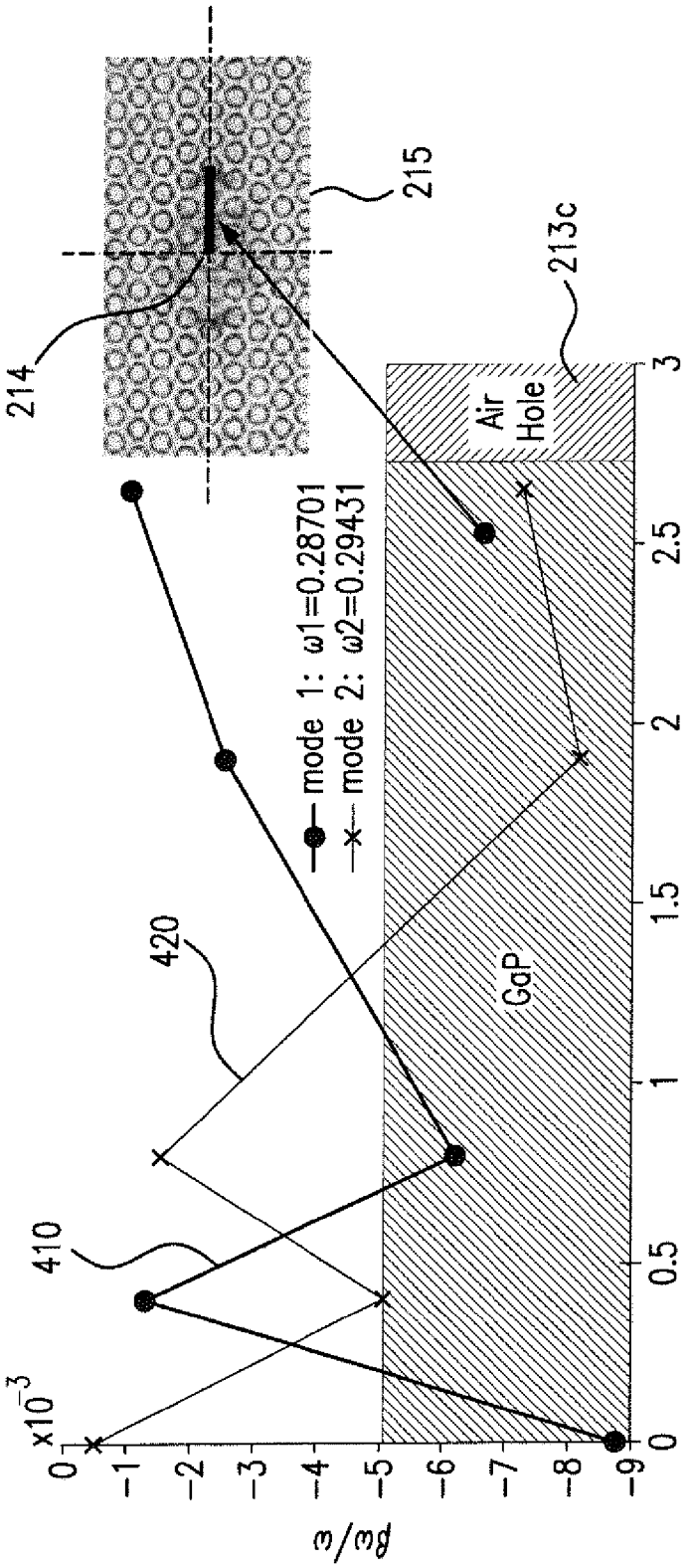

214
215
213c
Air Hole
GaP
420
410
mode 1: ω1=0.28701
mode 2: ω2=0.29431
x10^-3
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
0.5
1
1.5
2
2.5
3
Distance from the cavity center (unit a)
δω/ω

FIG. 4a

Fig. 4b

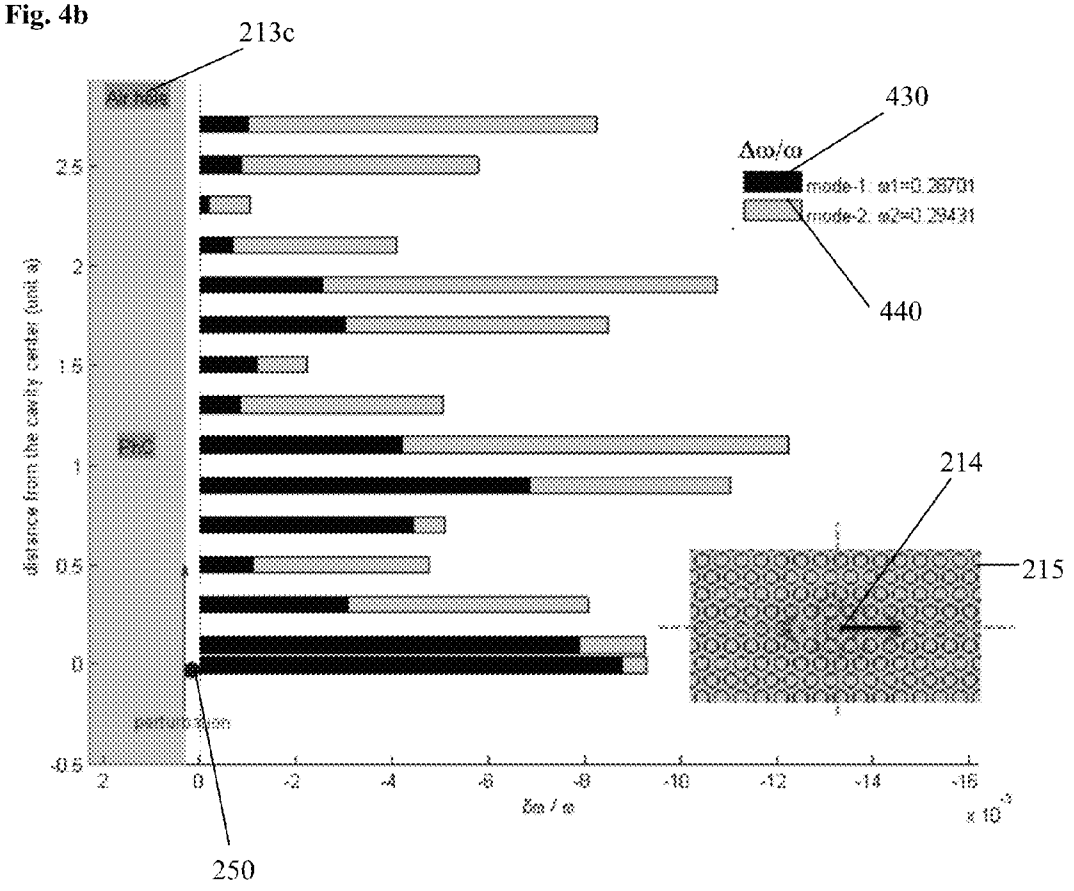

213c
430
Δω/ω
mode-1: ω1=0.28701
mode-2: ω2=0.29431
440
214
215
250
distance from the cavity center (unit a)
2.5
2
1.5
1
0.5
0
-0.5
2
0
-2
-4
-6
-8
-10
-12
-14
-16
Δω / ω
x 10^-3

Fig. 5

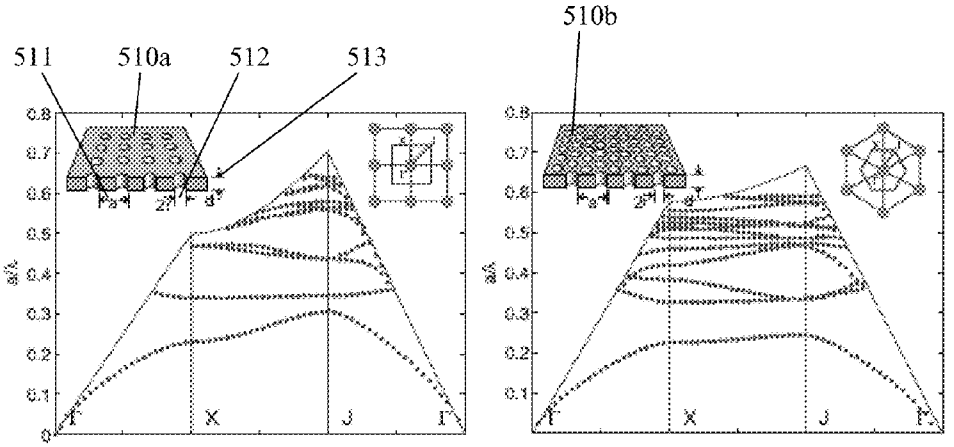


Fig. 6

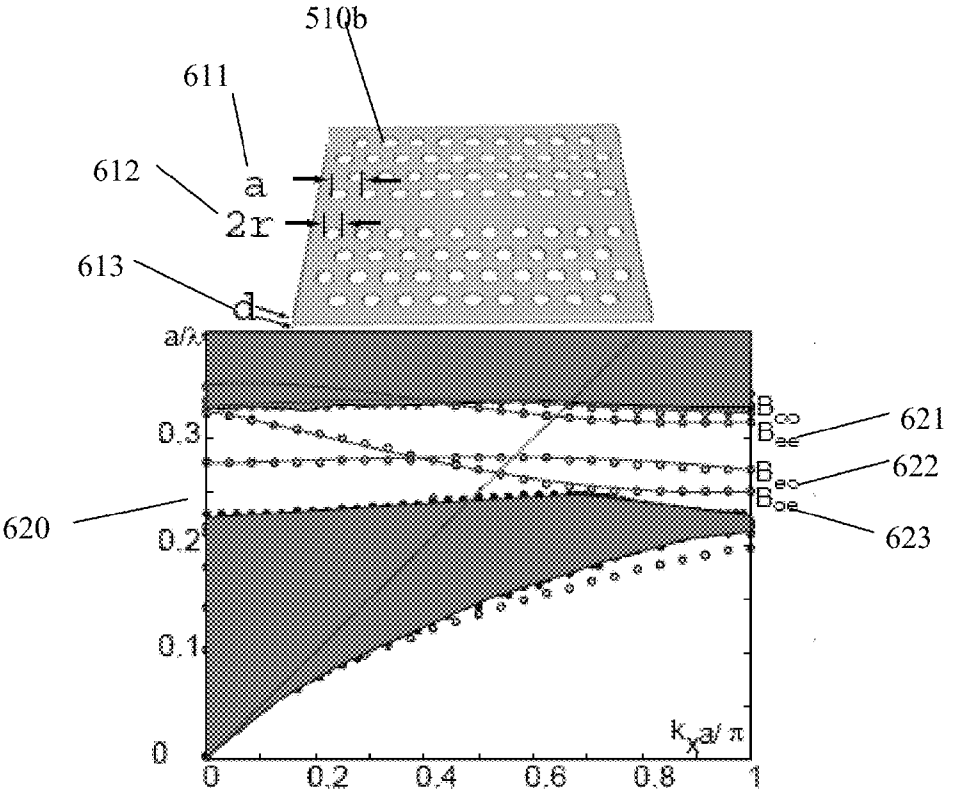

510b
611
612
a
2r
613
d
a/λ
0.3
0.2
0.1
0
620
621
622
623
B_{oo}
B_{ee}
B_{eo}
B_{oe}
$k_x a/\pi$
0
0.2
0.4
0.6
0.8
1

Fig. 7

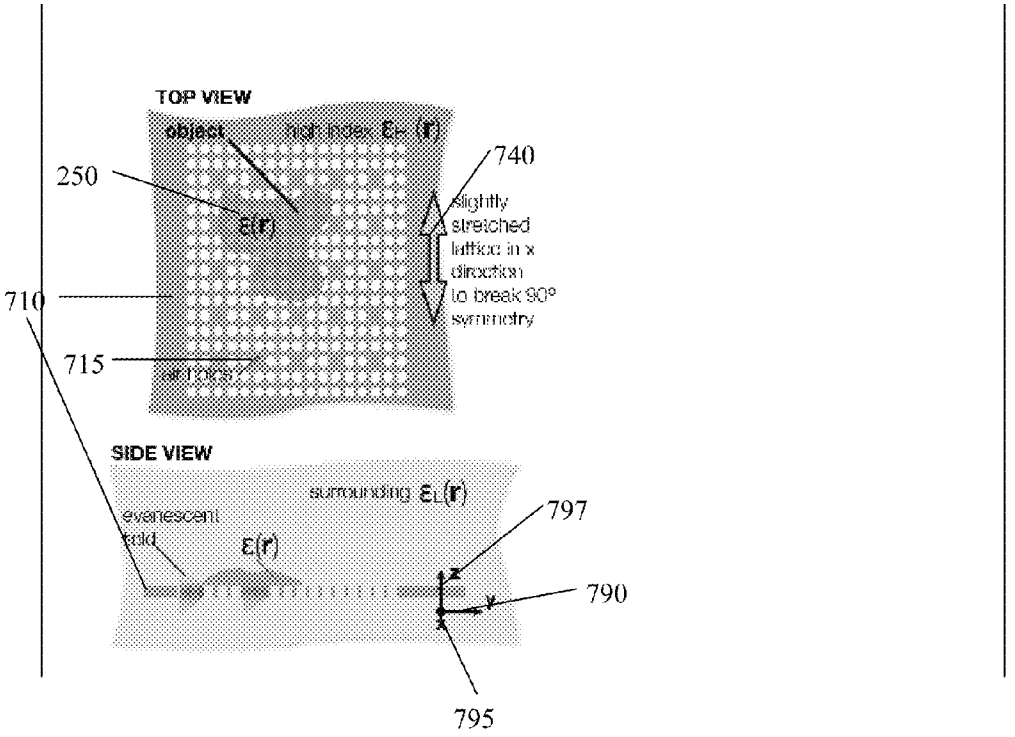
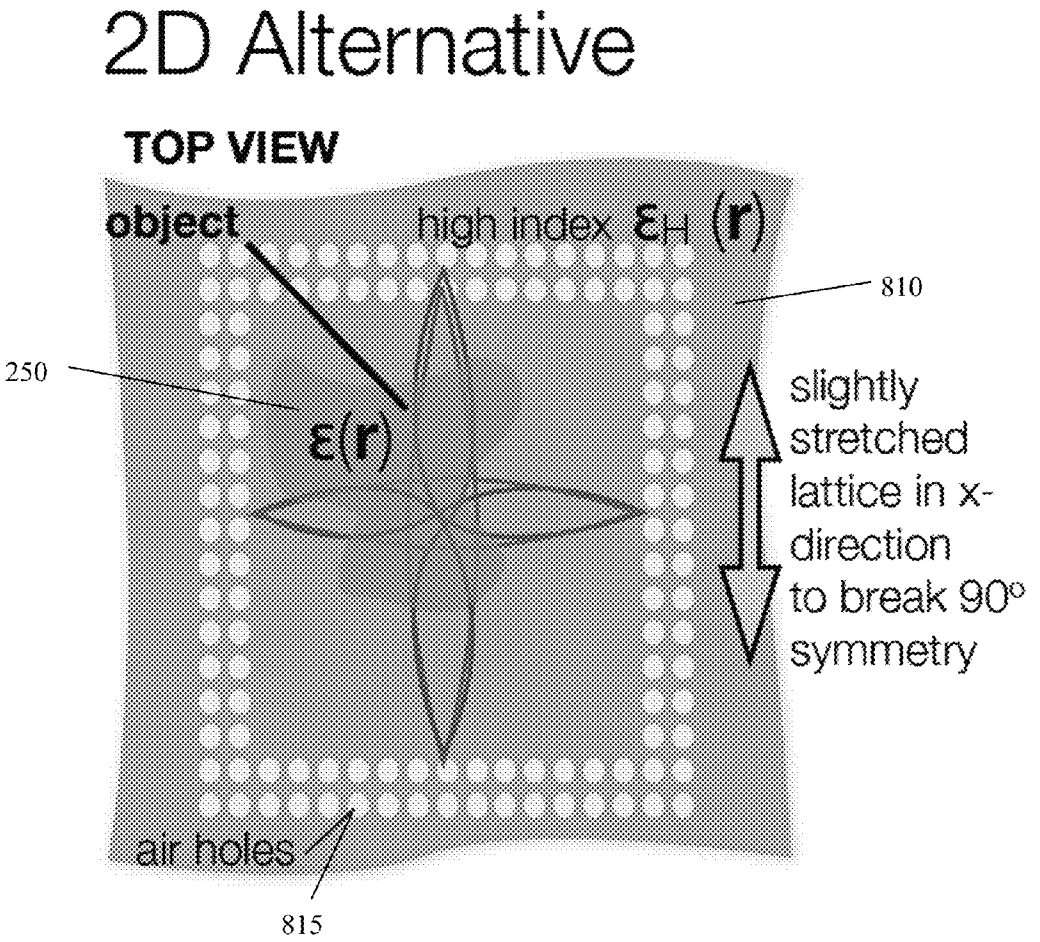

TOP VIEW
object
250
740
slightly
stretched
lattice in x
direction
to break 90°
symmetry
710
715
SIDE VIEW
surrounding
evanescent
field
797
790
795

Fig. 8


2D Alternative
TOP VIEW
object
high index ε_H (r)
810
250
ε(r)
slightly stretched lattice in x-direction to break 90° symmetry
air holes
815

LENS-FREE PLANAR IMAGER AND WIRELESS TRANSMITTER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of International Application No. PCT/US2012/048833 filed Jul. 30, 2012, which is related to U.S. Provisional Application Ser. No. 61/513,826, filed Aug. 1, 2011, each of which is incorporated herein by reference in its entirety and from which priority is claimed.

STATEMENT OF FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Grant No. PECASE # FA9550-12-1-0045, awarded by the Air Force Office of Scientific Research. The government has certain rights in the invention.

BACKGROUND

[0003] The disclosed subject matter relates generally to techniques for lens-free super-resolution imaging.

[0004] The field of optical microscopy includes systems with imaging optics, e.g., series of lenses that project an object plane onto an imaging-plane which, in turn, is typically recorded by an imaging array such as a CCD camera or the retina. However, in some applications, it can desirable to acquire an image without the use of lenses. For example, limited-space applications such as endoscopy can benefit from small, lens-free imaging systems.

[0005] Electromagnetic waves, including those in the infrared, visual, and ultraviolet spectrum, propagating through a medium can undergo frequency-dependent effects known as dispersion. For example, light traveling through a prism can undergo phase velocity dispersion, wherein different frequencies of light are refracted differently (i.e., different wavelengths have different propagation velocities). The "dispersion relation" can describe the relation of wave properties, such as for example wavelength, frequency, velocity, and refractive index of a medium. Dispersion relations can depend on material composition of a medium through which an electromagnetic wave travels, the geometry of the medium, and other factors.

[0006] Photonic crystals (PCs) can have peculiar optical properties, which can allow for the modification and engineering of the dispersion relation of the crystal for photons at optical frequencies. Photonic crystals can be fabricated to affect the motion of photons. For example, nanoscale waveguides can be created by introducing defects in a periodic structure. Optical cavities can be created by removing one or more holes in a PC lattice. Such cavities can be high-Q and can have desirable modal volume. Additionally, optical cavities can be designed to include more than one mode localized in the cavity area. Such modes can be referred to as standing wave moves, which can be composed of superpositions of forward and backward traveling Bloch modes. Each standing wave can have a unique spatial distribution, which can correspond to a different resonant frequency for each mode.

SUMMARY

[0007] In one aspect of the disclosed subject matter, a method for lens-free imaging using optical resonator includes providing a series of standing waves, each wave indexed by a wave vector k_i. The optical resonator can have a predetermined dispersion relation describing a relationship between the standing waves and the corresponding wave vector. The intensity of the resonances corresponding to wavelengths of the standing waves can be measured. A magnitude and shift of the resonances corresponding to each of the standing waves can be measured. From this information, spatial information in k-space can be determined from the magnitude and shift for each resonance, which can be measured in frequency, and linked to the wave vector k using an inversion relationship. A spatial transform can be applied to the spatial information in k-space to generate an image.

[0008] In one embodiment, the series of standing waves can be provided in an optical cavity in a photonic crystal, and light can be coupled into the cavity through one or more waveguides. The light coupled into the cavity can be, for example, between 600 and 650 nm, and further can be spectrally filtered prior to coupling into the cavity.

[0009] In one embodiment, the photonic crystal can be contacted with a sample to be imaged, thereby creating a change in magnitude and shift of at least one of the resonance frequencies, linked via the dispersion relation to a wave vector. The intensity of the standing waves can be measured by transmitting light at corresponding wavelengths through an optical fiber to a photodetector. Alternatively, intensity can be measured remotely by detecting light leakage from the cavity. Additionally or alternatively, the photonic crystal can have some gain medium that generates light through photoluminescence or electroluminescence, providing an internal source of illumination. The leakage of this light from the photonic crystal, either vertically into free space or through an output waveguide, can be recorded to reconstruct the object.

[0010] In another aspect of the disclosed subject matter, a system for lens-free imaging can include an optical resonator adapted to contain a series of standing waves, each wave indexed by a wave vector k_i. The optical resonator can have a predetermined dispersion relation describing a relationship between the standing waves and the corresponding wave vector. A photodetector can be configured to measure the intensity of wavelengths corresponding to the standing waves. A processor can be electrically coupled to the photodetector and configured to determine, using the predetermined dispersion relation, a magnitude and shift of the wave vector k corresponding to each of the standing waves. The processor can be configured to determine spatial information in k-space from the magnitude and shift of the wave vector k corresponding to each of the standing waves using an inversion relationship. The processor can be configured to apply a transform to the spatial information in k-space to generate an image.

[0011] In one embodiment, the optical resonator can be an optical cavity in a photonic crystal. A light source and one or more waveguides can be adapted to couple light from the light source into the optical cavity. The optical resonator can be contacted with a sample, thereby causing a shift and amplitude modulation of at least one of the standing waves. The optical resonator can be a one, two, or three-dimensional optical resonator.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. **1** is a flow diagram of a method for lens-free imaging in accordance with an embodiment of the disclosed subject matter.

[0013] FIG. **2***a* is a block diagram of a system for lens-free imaging in accordance with an embodiment of the disclosed subject matter.

[0014] FIG. **2***b* is a diagrammatic representation of an optical resonator for lens-free imaging in accordance with an embodiment of the disclosed subject matter.

[0015] FIG. **2***c* is a diagrammatic representation of another optical resonator for lens-free imaging in accordance with an embodiment of the disclosed subject matter.

[0016] FIG. **3** illustrates imaging a sample in accordance with an embodiment of the disclosed subject matter.

[0017] FIG. **4***a* illustrates imaging a sample in accordance with another embodiment of the disclosed subject matter.

[0018] FIG. **4***b* illustrates the intensity of standing waves of an optical resonator into k-space in accordance with an embodiment of the disclosed subject matter.

[0019] FIG. **5** illustrates the dispersion relation for a photonic crystal for use in lens-free imaging in accordance with an embodiment of the disclosed subject matter.

[0020] FIG. **6** illustrates the dispersion relation for a photonic crystal for use in lens-free imaging in accordance with anther embodiment of the disclosed subject matter.

[0021] FIG. **7** is a schematic representation of an optical resonator for use in two-dimensional lens-free imaging in accordance with an embodiment of the disclosed subject matter.

[0022] FIG. **8** is a schematic representation of an optical resonator for use in two-dimensional lens-free imaging in accordance with another embodiment of the disclosed subject matter.

[0023] Throughout the drawings, the same reference numerals and characters, unless otherwise stated, are used to denote like features, elements, components or portions of the illustrated embodiments. Moreover, while the disclosed subject matter will now be described in detail with reference to the Figs., it is done so in connection with the illustrative embodiments.

DETAILED DESCRIPTION

[0024] In one aspect of the disclosed subject matter, techniques for lens-free imaging include converting spatial information into spectral information using an optical resonator to set up a series of standing waves, which can be indexed by their longitudinal wave vectors k. A weakly absorbing specimen that interacts with the cavity field can modulate the standing waves through its refractive index and absorption, causing a shift and amplitude modulation in the modes with wave vectors k. Using the cavity medium's dispersion relation $\omega(k)$ that relates the light's frequency to the light's k-vector, this k-space modulation can be observed in the transmission spectrum of the cavity mode, given by $I(\omega)$. An inversion algorithm can be used to obtain the spatial information $\epsilon(z)$ from the modulated cavity spectrum $I(\omega)$.

[0025] The dispersion relation of a photonic crystal can be given in terms of angular frequency by $\omega=2\pi f$ and wave number $k=2\pi/\lambda$. Thus, a relationship between the dispersion relation $\omega(k)$ and the light's spatial frequency can be given by the dispersion relation, which can be computed for photonic crystals by numerical techniques such as finite difference time domain (FDTD) simulations.

[0026] For purposes of illustration, and not limitation, the dispersion relation characteristics of a photonic crystal will be described with reference to FIG. **5** and FIG. **6**. A photonic crystal **510** can be fabricated by periodically modulating the refractive index of a thin semiconductor slab. The periodic modulation can result in a square lattice **510***a* or a hexagonal lattice **510***b*, or any other suitable lattice shape. The periodic modulation can introduce an energy band-structure for light in two dimensions. Cavity modes can be formed by introducing linear defects into a closed off portion of the lattice, e.g., by introducing mirrors to confine a portion of the mode of a waveguide. The lattice can have periodicity a **511**, hole radius r **512**, and slab thickness d **513**. FIG. **5** depicts the TE-like mode band diagram for a square lattice **510***a* and hexagonal lattice **510***b* with r/a=0.4, d/a=0.55, and n=3.6. FIG. **6** depicts a plot of dispersion relation for a hexagonal waveguide formed in a hexagonal lattice **510***b* in the ΓJ direction, with r/a=0.3, d/a=0.65, and n=3.6.

[0027] The dispersion relation of each mode in an optical cavity can be sensitive to an index change in the cladding of the photonic crystal. Additionally, as disclosed herein, cavity modes in the photonic crystal bandgap medium can exhibit small group velocity, which can result in a nearly flat dispersion relation $\omega(k)$. That is, for example, a small range in frequency can correspond to a large range in k-vector. A large range in k-vectors can be important to map out both slowly varying and rapidly varying features of an image.

[0028] A small perturbation presented in the near field can cause the resonant modes of the cavity of the photonic crystal to respond differently, which can be presented by different resonant shifts corresponding to the position of the perturbation and/or amplitude modulation of the modes. As such and in accordance with the disclosed subject matter, a sub-wavelength feature can be mapped out by looking solely at k-space.

[0029] Particular embodiments of the method and system are described below, with reference to FIG. **1**, and FIG. **2***a*, FIG. **2***b*, FIG. **2***c* (collectively, FIG. **2**), for purposes of illustration, and not limitation. For purposes of clarity, the method and the system are described concurrently and in conjunction with each other.

[0030] An optical resonator **210** can be provided (**110**). The optical resonator **210** can be any suitable optical resonator. For example, in one embodiment, the optical resonator **210** can include two mirrors **211** reflective over a specified wavelength range given by the photonic crystal bandwidth, which can be controlled by the photonic crystal periodicity. Alternatively, the optical resonator **210** can include a photonic crystal **215** including a cavity **214**. The photonic crystal **215** can include a periodic structure of linear defects **213** with a different dielectric constant. The photonic crystal can be fabricated from, for example, silicon. Alternatively, the photonic crystal can be fabricated from a polymer, such as Poly(methyl methacrylate) (PMMA).

[0031] The optical resonator **210** can be configured to resonate at a set of frequencies. That is, the optical resonator can have a plurality of standing waves. Each wave can be indexed by its wave vector, k. The standing waves can generated by generating (**112**) light with a list source **240**. The light can then be filtered and/or processed (**114**) to achieve a desirable characteristic. For example, where the light source **240** emits broad-band light, spectral filters can be utilized to filter the light to a narrow band.

[0032] The light can then be coupled (**116**) into the optical resonator. For example, the light can be coupled (**116**) with the use of one or more waveguides. FIG. **2***b* provides an illustrative diagram of standing waves **212** in an optical resonator utilizing two reflective mirrors **211**. The wavelength of

the standing waves can be a multiple of the distance between the mirrors **211**. For example, the fundamental mode **212***a* and **212***c* can have a wavelength of d/2, where d is the optical path (refractive index times distance) between the mirrors **211**. The first mode **212***b* and **212***d* can have a wavelength of 2/4. Alternatively, the standing waves can correspond to characteristics of a cavity **214** in a photonic crystal **215**.

[0033] The optical resonator **210** can have a predetermined dispersion relation. In many cases, it can be desirable to employ a flat dispersion relation w(k) because a large range of spatial frequencies {k} are thus encoded into a narrow frequency spectrum {w}. A narrow frequency spectrum can simplify the optical system. As an example, a triangular holey 2D photonic crystal lattice with lattice spacing α, defined in a high-index material such as Si, can have a bandgap from a/λ=0.25-0.3. This frequency range can then be used for creating localized defect states in the 2D lattice. Then, waveguide, cavity, or coupled-cavity modes can define the dispersion relation. The dispersion relation can be tailored through the hole size near the defect regions. The relation can be tailored in such a way as to ensure a one-to-one correspondence between resonance frequencies of standing modes and k-states that constitute these standing waves. As described herein, the dispersion relation can represent a relationship between the standing waves and their corresponding wave vector. The dispersion relation can be predetermined based on the characteristics of the optical resonator **210**. For example, the geometry of the optical resonator and the refractive index of the medium in which it is contained can predetermine the dispersion relation. Moreover, where a photonic crystal is used as the optical resonator **210**, the photonic crystal can be designed to result in a desired dispersion relation.

[0034] In one embodiment, the photonic crystal can be designed to achieve a relatively flat dispersion relation, i.e., the derivative of the frequency w with respect to k is small. A value of dw/dk~0.01-0.1 c can be suitable, where c is the speed of light. That is, the cavity **214** of the photonic crystal **215** can be designed so that resonant modes can have small group velocity, whereby a small range in frequency corresponds to a large range in k.

[0035] The optical resonator **210** can be contacted (**120**) with a sample **250**. The position of the sample relative to the cavity can result in the perturbation and shift of resonance of difference modes. The techniques disclosed herein can, for example, map the change of index $\Delta\epsilon(\vec{r})=\Delta\epsilon_{real}(\vec{r})+i\cdot\Delta\epsilon_{image}(\vec{r})$ in space using Fourier transform for a small object present at the cavity region. The existence of small perturbation can result in a shift of resonance for each mode and an additional material loss, which can correspond to the broadening of quality factor Q. This relationship can be expressed, for example, using first order perturbation theory:

$$\frac{\Delta\omega_m}{\omega_m}\approx-\frac{1}{2}\frac{\int_V\Delta\varepsilon_{real,m}|E_m(\vec{r})|^2\,d\vec{r}}{\int_V\varepsilon_0|E_m(\vec{r})|^2\,d\vec{r}}, \tag{1}$$

where ϵ_0 is the dielectric constant of the cavity material, $\Delta\epsilon$ is the difference of the dielectric constant of the surrounding of the cavity with respect to the gas or liquid surrounding the cavity, and ϵ can be a function of position, r.

[0036] Thus, a resonance shift of each mode can be calculated. For perturbation in a relatively small size, the shift of resonance for a particular mode m, $\Delta\omega_m$ can depend on where it sits in the electric field of a mode m, $E_m(r)$. $\Delta\epsilon_m$ can be obtained so as to deduce the change in electrical permittivity by, for example, deducing from Q factor using the relationship:

$$\frac{1}{Q_{mat,m}}=\frac{1}{Q_{ptrb,m}}-\frac{1}{Q_{0,m}}, \tag{2}$$

where $Q_{0,m}$ is the original Q factor for mode m and can drop to $Q_{ptrb,m}$ with the presence of the small perturbation, which can introduce extra extrinsic loss denoted by the absorption coefficient $\alpha_{mat,m}$ as follows:

$$Q_{mat,m}=\frac{2\pi n_{pc}}{\alpha_{mat,m}\lambda_m} \tag{3}$$

[0037] The absorption coefficient $\alpha_{mat,m}=\gamma_{mat,m}/(c/n_{pc})$, and thus:

$$\gamma_{mat,m}=\omega_m\left(\frac{1}{Q_{ptrb,m}}-\frac{1}{Q_{0,m}}\right)^{-1} \tag{4}$$

[0038] The change in the imaginary part of $\Delta\epsilon_i(k)$ can be obtained by substituting equation 4 into equation 1:

$$\gamma_{mat,m}\approx-\frac{1}{2}\frac{\int_V\Delta\varepsilon_{imag,m}|E_m(\vec{r})|^2\,d\vec{r}}{\int_V\varepsilon_0|E_m(\vec{r})|^2\,d\vec{r}}. \tag{5}$$

[0039] Given the change in the complex electrical permittivity $\Delta\epsilon$ in k-space, a Fourier transform can be used to obtain $\Delta\epsilon(\vec{r})$:

$$\Delta\varepsilon(\vec{r})=\sum_m\Delta\varepsilon(\vec{k}_m)\exp(-i\vec{k}_m\cdot\vec{r})= \sum_m\left[\Delta\varepsilon_{real,m}(\vec{k}_m)+i\cdot\Delta\varepsilon_{imag,m}(\vec{k}_m)\right]\exp(-i\vec{k}_m\cdot\vec{r}). \tag{6}$$

[0040] The intensity of wavelengths corresponding to the standing waves can be measured (**130**). In one embodiment, the optical resonator **210** can be coupled to a photodetector **220** via one or more waveguides. The waveguides can be, for example, a photonic crystal with a pathway defined therein to guide (**132**) light from the optical resonator **210** to the photodetector **220**. Additionally or alternatively, light can be guided from the optical resonator **210** using one or more optical fibers. The fibers can be, for example, single mode fibers. Alternatively, the photodetector **220** can be adapted to receive light remotely (**134**) from light leakage from the optical resonator **210**.

[0041] The intensity spectrum of the optical cavity **210** can be converted (**140**) into k-space using the dispersion relation,

which can be deduced a-priori from numerical or analytical calculations. That is, a magnitude and shift of the wave vector k corresponding to each standing wave can be determined.

[0042] Spatial information, in k-space, can then be determined (**150**) based on the magnitude and shift of the wave vector k corresponding to each standing wave using an inversion relationship. The inversion relationship is given by the dispersion relation w(k). To simplify the inversion, w(k) can be single-valued, i.e., there exists unique pairs between a spatial frequency k (or −k) and w(k).

[0043] A transform can then be applied (**160**) to the spatial information in k-space to generate an image. In one embodiment, for example, the transform can be a fast Fourier transform. Each wave vector k can correspond to a coefficient in the fast Fourier transform. That is, each wave vector k can represent a phase (i.e., the resonant shift of the standing waves in the optical resonator **215**) and a magnitude (i.e., the amplitude of each standing wave in the optical resonator **215**). The transform can be given by the relationship

$$I(r) = c_0 \sum_{k=-\infty}^{\infty} e^{-ik*r} I(k),$$

where c_0 is a proportionality factor that is unimportant in this step.

[0044] The techniques disclosed herein can be employed in one, two, or three dimensions. For purposes of illustration, and not limitation, exemplary one dimensional imaging techniques will now be described.

[0045] With reference to FIG. **3**, a series of standing waves (**212***a*, **212***b* and **312**) can be set up in an optical resonator. A sample **250** can be contacted with the optical resonator at a location along the resonators axis (x). FIG. **3** includes a schematic representation **310** of intensity of the standing waves vs. position along the resonator axis. The sample **250** can be an emitter or an absorber. That is, for example, light in the cavity can interact with the sample **250** when it is contacted with a surface of the cavity. Additionally or alternatively, the sample **250** can have a refractive index different from that of the cavity medium, such that the light in the cavity can be modulated based on the sample's **250** refractive index. In this manner, certain standing waves can be modulated differently depending on the position of the sample **250**.

[0046] For example, where the resonator has three standing waves including the fundamental mode **212***a*, the first mode **212***b*, and the second mode **312**, the sample can be placed in the middle of the resonator. The sample **250** can absorb (or emit) some light at the fundamental wavelength **212***a* and the second wavelength **312**. However, the sample **250** can fail to interact with the first mode **212***b*.

[0047] The intensity of the standing waves (**212***a*, **212***b*, and **312**) can be detected in accordance with the disclosed subject matter and converted into k-space. FIG. **3** depicts a graph **330** of intensity in k-space vs wave vector k index. That is, the first wave vector **313***a* corresponding to the fundamental mode **212***a* has a low intensity due to interaction with the sample **250**. The second wave vector **313***b* has a high intensity due to the lack of interaction with the sample **250**. The third wave vector **313***c* has a low intensity due to interaction with the sample. In this manner, spatial information has been encoded intro spectral information. The k-space information can then be converted into spatial information using an inversion algorithm, and the spatial k-space information can be converted into an image by applying a transform.

[0048] With reference to FIGS. **4***a* and **4***b*, a cavity **214** in a photonic crystal **215** can have two even modes. The cavity **214** can exist by virtue of having 5 missing holes in the photonic crystal **215**. The two modes **410** and **420** can have different spatial distributions. According to equation 1, when the perturbation due to a sample **250** sits at some spot where mode 1 has maximum intensity while mode 2 has minimum intensity, they can exhibit different resonant shifts. Due to the strong nonlinear dispersion relation of the photonic crystal **215**, a small shift in frequency domain can be amplified in the spatial domain. FIG. **4***a* illustrates resonance shifts of the two modes **410** and **420** corresponding to the position of a perturbation (illustrated as at the center of the cavity **214**). FIG. **4***b* illustrates resonance shifts of the two modes **430** and **440** in k-space.

[0049] Because spatial information is converted into spectral information in accordance with the disclosed subject matter, an entire image can be automatically encoded in the spectrum, as in dense wavelength division multiplexing (DWDM). The image can thus be transmitted through a single mode waveguide, such as optical fiber. This feature can enable applications such as endoscopy with an ultra-small 2D planar PC imager (a 100 nm thick, microns wide sheet) coupled to a single mode optical fiber. Furthermore, images can be acquired remotely by light leakage from the photonic crystal: for instance, the photonic crystal can be embedded in a tissue. Upon optical excitation, it can emit the image of its local environment in the spectral domain, which can be recorded from outside the tissue, even in a diffusive medium.

[0050] In one embodiment, and with reference to FIG. **7** and FIG. **8** techniques for two dimensional lens-free imaging can include using a number of standing waves in x **795** and y **790** dimensions that have unique frequencies. For example, photonic crystal 2D coupled resonator array (PCCRA) **710** can be used. When the defects **715** within the array **710** are close enough together such that the defect modes overlap with the nearby cavity, some of the defect modes can be come coupled and a band forms. These bands can be described by a dispersion relation w(k), similar to that depicted in FIG. **6**, where k is the wave vector in the x **795**, y **790** plane, the z **797** axis being normal to the surface of the photonic crystal. Different lattice geometries can be used, including for example a square, triangular, or hexagonal lattice.

[0051] For purposes of illustration and not limitation, a square lattice **710** with single hole defects can be provided. The frequencies of standing waves with 90 degree rotated standing waves can be equal due to the 90 degree lattice symmetry. Such an equality can create an ambiguity in image reconstruction owing to the lack of unique relationship between the frequency w and wave vector k. In some embodiments, the degeneracy of these standing waves can be broken by, for example, changing the lattice spacing in the x and y directions to shift the resonance frequencies by approximately a cavity line width. For example, the photonic crystal can be stretched **740** along one axis by approximately 1% to approximately 2%.

[0052] In another embodiment, rather than a PCCRA, a 2d Fabry cavity **810** can be used, in which light can be configured within a 2D cavity bounded by defects to create a mirror **815**. In this embodiment, standing waves with low frequency can fall outside the reflection band of the mirror **815** surrounding

it. In certain embodiment, the mirror **815** can be a photonic crystal mirror, any other suitable type of dielectric mirror, or a metal mirror.

[0053] In like manner, techniques for three-dimensional lens-free imaging can include the use of a thee dimensional photonic crystal. Alternatively, a three dimensional open cavity can be employed. Degeneracy of the standing wave frequencies can be broken by slight asymmetries.

[0054] The ability to use DWDM recording equipment according to the presently disclosed techniques can lower costs and allow the entire system to be integrated in photonic integrated chips. 1D and 2D systems devices can be manufactured in a massively parallel fashion using previous generation optical lithography processing. Such optical lithography can project a mask onto a photosensitive film on the Si membrane sample to produce a copy. This copy can then be etched using a reactive ion plasma into the target sample, producing a photonic crystal pattern. A wet chemical etch can release a sacrificial layer underneath the Si membrane to release it from the substrate. The sacrificial layer can be, for example SiO2 for Silicon on Insulator wafers. Additionally, systems in accordance with the disclose subject matter can be used in a passive mode in which external light can be coupled into cavity modes. Alternatively, systems in accordance with the disclosed subject matter can be fabricated from light emitting material (e.g., III/V semiconductor materials), in which case an external pump beam can be used to internally illuminate standing waves in the device. Further, the system in accordance with the disclosed subject matter can be electrically pumped, removing the need for external illumination.

[0055] The resolution of an imaging system in accordance with the subject matter disclosed herein can be given by the smallest feature size of the standing wave, which can be below 50 nm.

[0056] The presently disclosed subject matter is not to be limited in scope by the specific embodiments herein. Indeed, various modifications of the disclosed subject matter in addition to those described herein will become apparent to those skilled in the art from the foregoing description and the accompanying figures. Such modifications are intended to fall within the scope of the appended claims.

1. A method for lens-free imaging using an optical resonator, comprising:

providing a series of standing waves, each wave indexed by a wave vector k_i, the optical resonator having a predetermined dispersion relation describing a relationship between the standing waves and the corresponding wave vector;

measuring the intensity of wavelengths corresponding to the standing waves;

determining, using the predetermined dispersion relation, a magnitude and shift of the wave vector k corresponding to each of the standing waves;

determining spatial information in k-space from the magnitude and shift of the wave vector k corresponding to each of the standing waves using an inversion relationship; and

applying a transform to the spatial information in k-space to generate an image.

2. The method of claim **1**, wherein the series of standing waves are provided in an optical cavity in a photonic crystal, and where providing further comprises coupling light through at least one waveguide into the cavity.

3. The method of claim **1**, wherein coupling the light through at least one waveguide further comprises directing the light through one or more spectral filters.

4. The method of claim **1**, wherein the light is between 600 and 650 nm.

5. The method of claim **1**, further comprising contacting the photonic crystal with a sample to be imaged, thereby creating a change in the magnitude and shift of at least one of the wave vectors.

6. The method of claim **5**, wherein the sample is a weakly absorbing sample with a refractive index different than a refractive index of the photonic crystal, and wherein determining the magnitude and shift of the wave vector k corresponding to each of the standing waves further comprises determining a shift and amplitude modulation based on a perturbation of the standing waves from the refractive index and an absorption characteristic of the sample.

7. The method of claim **5**, wherein the sample further comprises an emitter, whereby an emission of the emitter interacts with the standing waves of the optical cavity.

8. The method of claim **1**, wherein measuring the intensity of wavelengths further comprises transmitting the wavelengths through an optical fiber to a photodetector.

9. The method of claim **1**, wherein measuring the intensity of wavelengths further comprises measuring the intensity of wavelengths remotely by a light leakage from the photonic crystal.

10. The method of claim **1**, wherein the providing further comprises providing a multi-dimensional optical resonator with a series of standing waves in each dimension.

11. A system for lens-free imaging, comprising:

an optical resonator adapted to contain a series of standing waves, each wave indexed by a wave vector k_i, the optical resonator having a predetermined dispersion relation describing a relationship between the standing waves and the corresponding wave vector;

a photodetector configured to measure the intensity of wavelengths corresponding to the standing waves; and

a processor, electrically coupled to the photodetector, configured to determine, using the predetermined dispersion relation, a magnitude and shift of the wave vector k corresponding to each of the standing waves, configured to determine spatial information in k-space from the magnitude and shift of the wave vector k corresponding to each of the standing waves using an inversion relationship, and configured to apply a transform to the spatial information in k-space to generate an image.

12. The system of claim **11**, wherein the optical resonator is an optical cavity in a photonic crystal, further comprising:

a light source;

at least one waveguide for coupling light from the light source into the optical cavity.

13. The system of claim **11**, wherein the processor is further configured to determine, using the predetermined dispersion relation, a magnitude and shift of the wave vector k corresponding to each of the standing waves resulting from contacting the optical resonator with a sample to be imaged.

14. The system of claim **13**, wherein the sample is a weakly absorbing sample with a refractive index different than a refractive index of the optical resonator, and wherein the processor is further configured to determine the magnitude and shift of the wave vector k corresponding to each of the standing waves using a shift and amplitude modulation based

on a perturbation of the standing waves from the refractive index and an absorption characteristic of the sample.

15. The system of claim **11**, further comprising an optical fiber, optically coupled to the optical resonator and the photodetector, for transmitting the wavelengths corresponding to the standing waves.

16. The system of claim **11**, wherein the photodetector is configured to measure the intensity of wavelengths corresponding to the standing waves remotely by detecting a light leakage from the optical resonator.

17. The system of claim **11**, wherein the optical resonator further comprises a multi-dimensional optical resonator.

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