

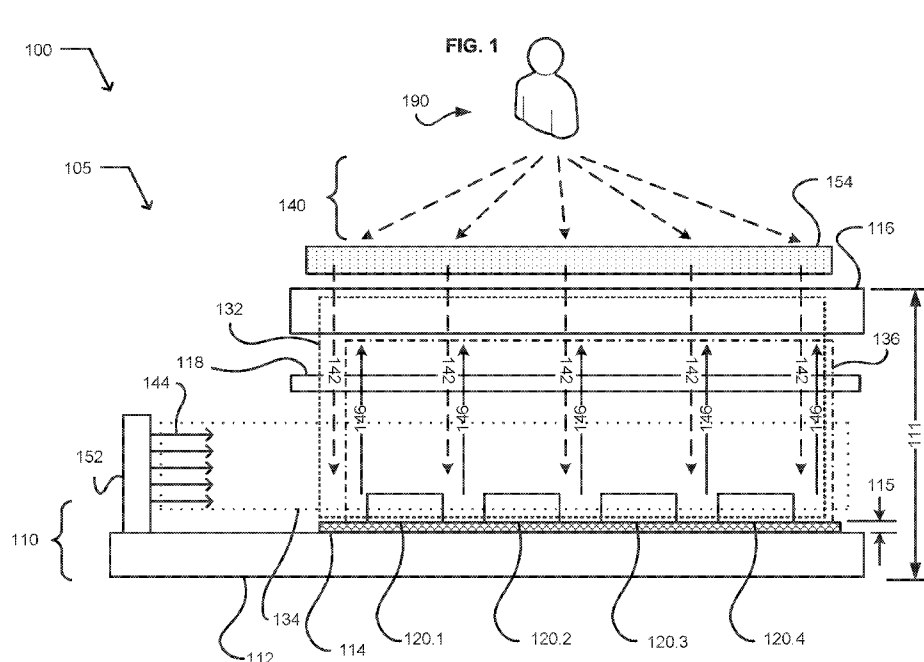
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(57) **Abstract:** Embodiments include an apparatus and method. An apparatus includes a metasurface that coherently upconverts light waves having a first frequency f_1 . A substrate forms a first plasmonic surface. A plasmonic nanoparticle forms a second plasmonic surface. A layer of a second-order nonlinear dielectric material is disposed between the first plasmonic surface and the second plasmonic surface. The metasurface has at least three plasmonic resonant modes including a first plasmonic resonant mode having a first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 . The apparatus includes a second light propagation path from a source of pumped monochromatic coherent light waves having the second frequency f_2 to the metasurface. A digital image capture device captures the generated light waves having the frequency f_3 .



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COHERENT UPCONVERSION OF LIGHT

5 [0001] All subject matter of the Priority Application(s) is incorporated herein by reference to the extent such subject matter is not inconsistent herewith.

Summary

[0002] For example, and without limitation, an embodiment of the subject matter described herein includes an apparatus. The apparatus includes a metasurface
10 configured to coherently upconvert incident light waves emanating from an object and having a first frequency f_1 . The metasurface includes a substrate having a first negative-permittivity layer comprising a first plasmonic surface. The metasurface includes a plasmonic nanoparticle having a base with a second negative-permittivity layer comprising a second plasmonic surface. The metasurface includes a dielectric
15 layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface. The metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having a first frequency f_1 , a second plasmonic resonant mode having a second
20 frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 . The metasurface is further configured to generate by a second order parametric process coherent light having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 . The apparatus includes a second light propagation path from a source of pumped monochromatic coherent light waves having the second frequency
25 f_2 to the metasurface. The apparatus includes a digital image capture device substantially transparent to light waves having the first frequency f_1 and configured to capture the generated light waves having the frequency f_3 .

[0003] In an embodiment, the apparatus includes a first light propagation path transmitting the light waves emanating from the object and having the first frequency
30 f_1 to the metasurface. In an embodiment, the apparatus includes a third light

propagation path transmitting the generated light waves having the third frequency f_3 from the metasurface to the digital image capture device. In an embodiment, the apparatus includes a band block filter configured to block light at the second frequency f_2 and interposed in the third light propagation path between the metasurface and the digital image capture device. In an embodiment, the apparatus includes a source of pumped monochromatic coherent light waves having the second frequency f_2 and optically coupled with the second light propagation path. In an embodiment, the apparatus includes a lens configured to focus the light waves emanating from the object onto the metasurface.

10 [0004] In an embodiment, the metasurface includes a substrate having a first negative-permittivity layer comprising a first plasmonic surface. The metasurface includes at least two plasmonic nanoparticles, each plasmonic nanoparticle of the at least two plasmonic nanoparticles having a respective base with a second negative-permittivity layer comprising a second plasmonic surface. The dielectric layer
15 includes a second-order nonlinear material disposed between the first plasmonic surface and the respective second plasmonic surface of each of the at least two plasmonic nanoparticles. The metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having a first frequency f_1 , a second
20 plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 . The metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 .

[0005] For example, and without limitation, an embodiment of the subject matter
25 described herein includes an apparatus. The apparatus includes a metasurface configured to coherently upconvert light waves emanating from an object and having a first frequency f_1 . The metasurface includes a substrate having a first negative-permittivity layer comprising a first plasmonic surface. The metasurface includes a plasmonic nanoparticle having a base with a second negative-permittivity layer
30 comprising a second plasmonic surface. The metasurface includes a dielectric layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface. The metasurface is configured to

form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 . The metasurface is further
5 configured to generate by a second order parametric process coherent light waves with a frequency having the third frequency f_3 that is a sum of first frequency f_1 and the second frequency f_2 . The apparatus includes a first light propagation path transmitting the light waves emanating from the object and having the first frequency f_1 to the metasurface. The apparatus includes a pumped laser outputting a
10 monochromatic coherent light having the second frequency f_2 . The apparatus includes a second light propagation path transmitting monochromatic coherent light having the second frequency f_2 from the pumped laser to the metasurface. The apparatus includes a digital image capture device substantially transparent to the light waves having the first frequency f_1 , and configured to (i) capture the generated light waves
15 having the third frequency f_3 and (ii) output an image responsive to the light waves emanating from the object. The apparatus includes a third light propagation path transmitting the generated light waves having the third frequency f_3 from the metasurface to the digital image capture device.

[0006] For example, and without limitation, an embodiment of the subject
20 matter described herein includes a method. The method includes simultaneously receiving in a thin planar metasurface (i) light waves emanating from an object and having a first frequency f_1 and (ii) pumped monochromatic coherent light waves having a second frequency f_2 . The method includes non-linearly combining in the thin planar metasurface the light waves having the first frequency f_1 and the pumped
25 monochromatic coherent light waves having the second frequency f_2 . The method includes generating in the thin planar metasurface by a second order parametric process coherent light waves having a third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 . The method includes digitizing the generated light waves having the frequency f_3 . The method includes outputting in
30 response to the digitized generated light waves a digital image responsive to the light waves emanating from the object. In an embodiment, the method includes blocking light waves at the second frequency f_2 from reaching the digital image capture device.

[0007] The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description.

5

Brief Description of the Drawings

FIG. 1 schematically illustrates an example environment in which embodiments may be implemented;

FIG. 2 schematically illustrates a top view of an embodiment of the plasmonic nanoparticle of the apparatus;

10 FIG. 3 illustrates an example operational flow;

FIG. 4 schematically illustrates an example environment in which embodiments may be implemented;

FIG. 5 schematically illustrates a top view of an embodiment of the first plasmonic nanoparticle, illustrated by the plasmonic nanoparticle, and the second plasmonic nanoparticle, illustrated by the plasmonic nanoparticle;

15

FIG. 6 illustrates an example operational flow;

FIG. 7 illustrates an environment that includes the object and an apparatus; and

FIG. 8 illustrates an example operational flow.

Detailed Description

20 [0008] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes
25 may be made, without departing from the spirit or scope of the subject matter presented here.

[0009] Those having skill in the art will recognize that the state of the art has progressed to the point where there is little distinction left between hardware, software,

and/or firmware implementations of aspects of systems; the use of hardware, software, and/or firmware is generally (but not always, in that in certain contexts the choice between hardware and software can become significant) a design choice representing cost vs. efficiency tradeoffs. Those having skill in the art will appreciate that there are various implementations by which processes and/or systems and/or other technologies described herein can be effected (e.g., hardware, software, and/or firmware), and that the preferred implementation will vary with the context in which the processes and/or systems and/or other technologies are deployed. For example, if an implementer determines that speed and accuracy are paramount, the implementer may opt for a mainly hardware and/or firmware implementation; alternatively, if flexibility is paramount, the implementer may opt for a mainly software implementation; or, yet again alternatively, the implementer may opt for some combination of hardware, software, and/or firmware. Hence, there are several possible implementations by which the processes and/or devices and/or other technologies described herein may be effected, none of which is inherently superior to the other in that any implementation to be utilized is a choice dependent upon the context in which the implementation will be deployed and the specific concerns (e.g., speed, flexibility, or predictability) of the implementer, any of which may vary. Those skilled in the art will recognize that optical aspects of implementations will typically employ optically-oriented hardware, software, and or firmware.

[0010] In some implementations described herein, logic and similar implementations may include software or other control structures suitable to implement an operation. Electronic circuitry, for example, may manifest one or more paths of electrical current constructed and arranged to implement various logic functions as described herein. In some implementations, one or more media are configured to bear a device-detectable implementation if such media hold or transmit a special-purpose device instruction set operable to perform as described herein. In some variants, for example, this may manifest as an update or other modification of existing software or firmware, or of gate arrays or other programmable hardware, such as by performing a reception of or a transmission of one or more instructions in relation to one or more operations described herein. Alternatively, or additionally, in some variants, an implementation may include special-purpose hardware, software,

firmware components, and/or general-purpose components executing or otherwise invoking special-purpose components. Specifications or other implementations may be transmitted by one or more instances of tangible transmission media as described herein, optionally by packet transmission or otherwise by passing through distributed media at various times.

[0011] Alternatively or additionally, implementations may include executing a special-purpose instruction sequence or otherwise invoking circuitry for enabling, triggering, coordinating, requesting, or otherwise causing one or more occurrences of any functional operations described below. In some variants, operational or other logical descriptions herein may be expressed directly as source code and compiled or otherwise invoked as an executable instruction sequence. In some contexts, for example, C++ or other code sequences can be compiled directly or otherwise implemented in high-level descriptor languages (e.g., a logic-synthesizable language, a hardware description language, a hardware design simulation, and/or other such similar mode(s) of expression). Alternatively or additionally, some or all of the logical expression may be manifested as a Verilog-type hardware description or other circuitry model before physical implementation in hardware, especially for basic operations or timing-critical applications. Those skilled in the art will recognize how to obtain, configure, and optimize suitable transmission or computational elements, material supplies, actuators, or other common structures in light of these teachings.

[0012] In a general sense, those skilled in the art will recognize that the various embodiments described herein can be implemented, individually and/or collectively, by various types of electro-mechanical systems having a wide range of electrical components such as hardware, software, firmware, and/or virtually any combination thereof; and a wide range of components that may impart mechanical force or motion such as rigid bodies, spring or torsional bodies, hydraulics, electro-magnetically actuated devices, and/or virtually any combination thereof. Consequently, as used herein “electro-mechanical system” includes, but is not limited to, electrical circuitry operably coupled with a transducer (e.g., an actuator, a motor, a piezoelectric crystal, a Micro Electro Mechanical System (MEMS), etc.), electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical

circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of memory (e.g., random access, flash, read only, etc.)), electrical circuitry forming a communications device (e.g., a modem, module, communications switch, optical-electrical equipment, etc.), and/or any non-electrical analog thereto, such as optical or other analogs. Those skilled in the art will also appreciate that examples of electro-mechanical systems include but are not limited to a variety of consumer electronics systems, medical devices, as well as other systems such as motorized transport systems, factory automation systems, security systems, and/or communication/computing systems. Those skilled in the art will recognize that electro-mechanical as used herein is not necessarily limited to a system that has both electrical and mechanical actuation except as context may dictate otherwise.

[0013] In a general sense, those skilled in the art will also recognize that the various aspects described herein which can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, and/or any combination thereof can be viewed as being composed of various types of “electrical circuitry.” Consequently, as used herein “electrical circuitry” includes, but is not limited to, electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of memory (e.g., random access, flash, read only, etc.)), and/or electrical circuitry forming a communications device (e.g., a modem, communications switch, optical-electrical equipment, etc.). Those having skill in the art will recognize that the subject matter described herein may be implemented in an analog or digital fashion or some combination thereof.

[0014] Those skilled in the art will further recognize that at least a portion of the devices and/or processes described herein can be integrated into an image processing system. A typical image processing system may generally include one or more of a system unit housing, a video display device, memory such as volatile or non-volatile memory, processors such as microprocessors or digital signal processors, computational entities such as operating systems, drivers, applications programs, one or more interaction devices (e.g., a touch pad, a touch-sensitive screen or display surface, an antenna, etc.), control systems including feedback loops and control motors (e.g., feedback for sensing lens position and/or velocity; control motors for moving/distorting lenses to give desired focuses). An image processing system may be implemented utilizing suitable commercially available components, such as those typically found in digital still systems and/or digital motion systems.

[0015] Those skilled in the art will likewise recognize that at least some of the devices and/or processes described herein can be integrated into a data processing system. Those having skill in the art will recognize that a data processing system generally includes one or more of a system unit housing, a video display device, memory such as volatile or non-volatile memory, processors such as microprocessors or digital signal processors, computational entities such as operating systems, drivers, graphical user interfaces, and applications programs, one or more interaction devices (e.g., a touch pad, a touch-sensitive screen or display surface, an antenna, etc.), and/or control systems including feedback loops and control motors (e.g., feedback for sensing position and/or velocity; control motors for moving and/or adjusting components and/or quantities). A data processing system may be implemented utilizing suitable commercially available components, such as those typically found in data computing/communication and/or network computing/communication systems.

[0016] Computer-readable media may include any media that can be accessed by a computing device and include non-transitory media, both volatile and nonvolatile media, and removable and non-removable media. By way of example, and not of limitation, computer-readable media may include computer storage media. Computer storage media includes nonvolatile, removable and non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules, or other data. Computer storage media

includes, but is not limited to, random-access memory (RAM), read-only memory (ROM), electrically erasable programmable read-only memory (EEPROM), flash memory, or other memory technology, CD-ROM, digital versatile disks (DVD), or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage, or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by the computing device. In a further embodiment, a computer storage media may include a group of computer storage media devices. In another embodiment, a computer storage media may include an information store. In another embodiment, an information store may include a quantum memory, a photonic quantum memory, or atomic quantum memory. Combinations of any of the above may also be included within the scope of computer-readable media.

[0017] In certain instances, one or more elements of disclosed embodiments may be deemed not necessary and omitted. In other instances, one or more other elements of disclosed embodiments may be deemed necessary and added.

[0018] FIG. 1 schematically illustrates an example environment 100 in which embodiments may be implemented. The environment includes an apparatus 105 and an object to be imaged 190. While the object is illustrated as a human, in other embodiments the object may include for example an animal, a tissue sample, a material, a composition, vehicle, or an airborne device. The apparatus 105 includes a metasurface 110 configured to coherently upconvert incident light waves emanating from the object 190 and having a first frequency f_1 . The incident light waves are schematically illustrated as light waves 142 within the apparatus, and as light waves 140 between the object 190 and the apparatus, which may be light waves in free space. In an embodiment, the first frequency f_1 is a frequency of infrared light waves. In an embodiment, the first frequency f_1 is a frequency of optical light waves. In an embodiment, the light waves emanating from the object include light waves emitted by, reflected from, or transmitted by the object. The metasurface includes a substrate 112 having a first negative-permittivity layer comprising a first plasmonic surface. In an embodiment, the metasurface includes an optically thin ($\ll f_1$) array of sub-wavelength size ($\ll \lambda$), and sub-wavelength ($\ll \lambda$) spaced plasmonic nanoparticles. In an embodiment, the metasurface includes an optically thin subwavelength structured

interface. The metasurface includes a plasmonic nanoparticle having a base with a second negative-permittivity layer comprising a second plasmonic surface. The plasmonic nanoparticle is schematically illustrated by plasmonic nanoparticle 120.1. In an embodiment, the metasurface may include at least two plasmonic nanoparticles, schematically illustrated by the plasmonic nanoparticles 120.1-120.4.

[0019] The metasurface 110 includes a dielectric layer 114 comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface of the plasmonic nanoparticle, illustrated by the plasmonic nanoparticle 120.1. The dielectric layer has a thickness 115. The metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 . The metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 . For example, in an embodiment, if the first frequency f_1 is 100 THz, and if the second frequency f_2 is 282 THz, the third frequency f_3 will be 382 THz.

[0020] The apparatus 105 includes a second light propagation path, schematically illustrated as second light propagation path 134, from a source 152 of pumped monochromatic coherent light waves 144 having the second frequency f_2 to the metasurface 110. In an embodiment, the second light propagation path may include a free space path. In an embodiment, the second light propagation path may include a light conductive medium, glass, or fiber path. In an embodiment, the second light propagation path may include a combination of at least two paths. For example, a combination path may include at least one of a free space, glass, or fiber paths. The apparatus includes a digital image capture device 116 substantially transparent to the light waves 140 and 142 having the first frequency f_1 and configured to capture the generated light waves having the frequency f_3 . In an embodiment, substantially transparent includes greater than 90% transmission at the first frequency f_1 . In an embodiment, substantially transparent includes greater than 80% transmission at the first frequency f_1 . In an embodiment, substantially transparent includes greater than

60% transmission at the first frequency f_1 . In an embodiment, substantially transparent includes greater than 40% transmission at the first frequency f_1 . For example the substantial transparency of digital image capture device may be provided by Si, InGaAs, or other material having an energy band gap at f_1 . In an embodiment, the digital image capture device may include a bulk-optics system.

[0021] In an embodiment, the apparatus 105 includes a first light propagation path, schematically illustrates as first light propagation path 132 transmitting the light waves 142 emanating from the object 190 and having the first frequency f_1 to the metasurface 110. In an embodiment, the first light propagation path may include a free space path. In an embodiment, the first light propagation path may include a light conductive medium, glass, or fiber path. In an embodiment, the first light propagation path may include a combination of at least two paths. For example, a combination path may include at least one of a free space, glass, or fiber paths. In an embodiment, the apparatus includes a third light propagation path, schematically illustrated as third light propagation path 136, transmitting the generated light waves 146 having the third frequency f_3 from the metasurface to the digital image capture device 116. In an embodiment, the apparatus includes a band block filter 118 configured to block light waves 144 at the second frequency f_2 and interposed in the third light propagation path 136 between the metasurface 110 and the digital image capture device 116. In an embodiment, the third light propagation path includes at least a portion of the first light propagation path 132 transmitting the light waves 142 emanating from the object 190 toward the metasurface.

[0022] In an embodiment, the apparatus 105 includes a source 152 of the pumped monochromatic coherent light waves 144 having the second frequency f_2 and optically coupled with the second light propagation path 134. In an embodiment, the source includes a pumped laser outputting the pumped monochromatic coherent light waves having the second frequency f_2 . In an embodiment, the pumped laser includes a tunable pumped laser. In an embodiment, the apparatus includes a lens 154 configured to focus the light waves 140 emanating from the object 190 onto the metasurface 110. In an embodiment, the lens includes a flat or planar lens. In an embodiment, the lens includes a metamaterial lens. In an embodiment, the lens includes a bulk optics lens.

[0023] In an embodiment, the first plasmonic resonant mode frequency f_1 is spectrally separated from the second plasmonic resonant mode frequency f_2 . In an embodiment, the first plasmonic resonant mode frequency f_1 is a function of a first characteristic of the plasmonic nanoparticle. The second plasmonic resonant mode frequency f_2 is a function of a second characteristic of the plasmonic nanoparticle. The third plasmonic resonant mode frequency f_3 is a function of both the first characteristic of the plasmonic nanoparticle and the second characteristic of the plasmonic nanoparticle. In an embodiment, the first characteristic of the plasmonic nanoparticle includes a first structural characteristic of the plasmonic nanoparticle and the second characteristic of the plasmonic nanoparticle includes a second structural characteristic of the plasmonic nanoparticle. In an embodiment, the first characteristic of the plasmonic nanoparticle includes a first dimensional characteristic of the plasmonic nanoparticle and the second characteristic of the plasmonic nanoparticle includes a second dimensional characteristic of the plasmonic nanoparticle.

[0024] FIG. 2 schematically illustrates a top view of an embodiment of the plasmonic nanoparticle of the apparatus 105, illustrated by the plasmonic nanoparticle 120.1. In an embodiment, the first plasmonic resonant mode frequency f_1 is a function of a first side dimension 122 of a non-square rectangular base of the plasmonic nanoparticle. FIG. 2 schematically illustrates regions of the first plasmonic resonance mode as regions 123.1 and 123.2. In an embodiment, the second plasmonic resonant mode frequency f_2 is a function of a second side dimension 124 of the non-square rectangular base of the plasmonic nanoparticle. FIG. 2 schematically illustrates regions of the first plasmonic resonance mode as regions 125.1 and 125.2. In an embodiment, the third plasmonic resonant mode frequency f_3 is a function of both the first side dimension of the non-square rectangular base of the plasmonic nanoparticle and the second side dimension of the non-square rectangular base of the plasmonic nanoparticle. The schematic illustrations of the plasmonic resonance modes may or may not be representative of a location or locations of the actual the plasmonic resonance modes.

[0025] In an embodiment, the plasmonic nanoparticle, illustrated by the plasmonic nanoparticle 120.1, includes a base having a first characteristic, illustrated by the first side dimension 122, which in combination with the dielectric layer 114

establishes a first spatial mode at the first plasmonic resonant mode frequency f_1 . The base has a second characteristic, illustrated by the second side dimension 124, which in combination with the dielectric layer establishes a second spatial mode at the second plasmonic resonant mode frequency f_2 . The first spatial resonant mode and the second spatial resonant mode overlapping each other in the dielectric layer and creating the third plasmonic resonant mode having the third frequency f_3 . The spatial overlapping regions or third plasmonic resonance modes are illustrated as regions 128.1-128.4. The respective schematic illustration of the plasmonic resonance modes may or may not be representative of actual the plasmonic resonance modes.

[0026] In an embodiment, the first side dimension 122 is greater than the thickness 115 of the dielectric layer 114 illustrated in FIG. 1. In an embodiment, the first side dimension is much greater than the thickness of the dielectric layer. For example, in an embodiment, “much greater” means the first side dimension is at least five times greater than the thickness of the dielectric layer. In an embodiment, the second side dimension 124 is greater than the thickness of the dielectric layer. In an embodiment, the second side dimension 124 is much greater than the thickness of the dielectric layer. For example, in an embodiment, “much greater” means the second side dimension is at least five times greater than the thickness of the dielectric layer. In an embodiment, the plasmonic nanoparticle includes a non-square rectangular base having (i) a first dimension characteristic that establishes a first spatial electromagnetic field mode at the first plasmonic resonant mode frequency f_1 and (ii) a second dimension characteristic that establishes a second spatial electromagnetic field mode at the second plasmonic resonant mode frequency f_2 . The first spatial electromagnetic mode and the second spatial electromagnetic mode overlapping each other in the dielectric layer and creating the third plasmonic resonant mode having the third frequency f_3 . In an embodiment, the base of the plasmonic nanoparticle includes a first dimension characteristic, for example the length of first side 122 that in combination with the dielectric layer establishes a first gap-plasmon guided mode. In an embodiment, the length of the first dimension is much greater than the thickness of dielectric gap. An example of a gap-plasmon guided mode is described in D. Smith, et al., Apparatus and method for providing a selectively absorbing structure, US 20150062686. In an embodiment, the base of the plasmonic nanoparticle includes a

second dimension characteristic, for example the length of the second side 124, that in combination with the dielectric layer establishes a second gap-plasmon guided mode. In an embodiment, the length of the second dimension characteristic is much greater than the thickness of dielectric gap. The schematic illustrations of the plasmonic resonance modes may or may not be representative of actual the plasmonic resonance modes.

[0027] Returning to FIG. 1, in the metasurface 110, the first plasmonic resonant mode frequency f_1 and the second plasmonic resonant mode frequency f_2 are a function of the second-order nonlinear dielectric material of the dielectric layer 114 disposed between the first plasmonic surface of the substrate 112 and the second plasmonic surface of the plasmonic nanoparticle, illustrated by the plasmonic nanoparticle 120.1. In an embodiment, the digital image capture device is further configured to output a digital image responsive to the light waves 140 & 142 emanating from the object 190.

[0028] In an embodiment, the metasurface 110 includes the substrate 112 having a first negative-permittivity layer comprising a first plasmonic surface. The metasurface includes at least two plasmonic nanoparticles, illustrated by the four plasmonic nanoparticles 120.1-120.4. Each plasmonic nanoparticle of the at least two plasmonic nanoparticles having a respective base with a second negative-permittivity layer comprising a second plasmonic surface. The dielectric layer 114 including a second-order nonlinear material disposed between the first plasmonic surface and the respective second plasmonic surface of each of the at least two plasmonic nanoparticles. The metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having the second frequency f_2 , and a third plasmonic resonant mode having the third frequency f_3 . The metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 .

[0029] In an embodiment, both the substrate 112 and the base of the plasmonic nanoparticle 120.1 have a parallel planar geometry. In an embodiment, the metasurface 110 includes a planar metasurface. In an embodiment, the metasurface

includes a flat panel metasurface. In an embodiment, the flat panel metasurface includes a curved flat panel metasurface. In an embodiment, the metasurface includes a metasurface formed on a silicon chip. In an embodiment, the metasurface includes a metasurface on a chip integrated platform.

5 [0030] In an embodiment, the apparatus 105 includes a planar apparatus. In an embodiment, the apparatus includes a flat panel apparatus. In an embodiment, the apparatus is formed on a silicon chip. In an embodiment, the apparatus is formed on a CMOS chip. In an embodiment, the apparatus includes on a chip integrated platform. In an embodiment, the apparatus has a thickness 111 less than 10 mm. In an
10 embodiment, the apparatus has a thickness less than of 5 mm. In an embodiment, the apparatus has a thickness of less than 1 mm. In an embodiment, the apparatus has a thickness of less than 0.5 mm. In an embodiment, the metasurface 110 includes an optically thin metasurface. For example, an optically thin metasurface includes the metasurface having a subwavelength thickness relative to f_1 or f_2 .

15 [0031] In an embodiment, the base of the plasmonic nanoparticle 120.1 is substantially conformal to the first plasmonic surface of the substrate 112. In an embodiment, the base of the plasmonic nanoparticle is substantially planar. In an embodiment, the base of the plasmonic nanoparticle has a major side, and a minor side shorter than the major side. In an embodiment, the major side corresponds to a base
20 dimension in a first direction and the minor side corresponds to a shorter base dimension in a non-aligned second direction. In an embodiment, the non-aligned second direction is at least substantially perpendicular to the first direction. In an embodiment, the plasmonic nanoparticle includes at least two joined or proximate plasmonic nanoparticles forming the single base with a second negative-permittivity
25 layer comprising the second plasmonic surface. In an embodiment, the at least two joined or proximate plasmonic nanoparticles form a non-square rectangular base with a second negative-permittivity layer comprising a second plasmonic surface. In an embodiment, the plasmonic nanoparticle includes a nanorod having a non-square rectangular base with the second negative-permittivity layer. In an embodiment, the
30 base of the plasmonic nanoparticle includes at least one of a rectangular, an ellipsoidal, or a triangular shaped base. In an embodiment, the base of the plasmonic nanoparticle has an elongated shaped base. In an embodiment, the base of the plasmonic

nanoparticle has an arbitrary shaped base. In an embodiment, the base of the plasmonic nanoparticle has a major side length between about 1000 and about 5000 nm. In an embodiment, the base of the plasmonic nanoparticle has a major side length between about 1500 and about 4000 nm. In an embodiment, the base of the plasmonic nanoparticle has a minor side length between about 500 and about 2000 nm.

[0032] In an embodiment, the dielectric layer 114 includes a dielectric layer region. In an embodiment, the dielectric layer includes a dielectric filled gap. In an embodiment, the second-order nonlinear dielectric material of the dielectric layer includes a potassium titanyl phosphate (KTP). In an embodiment, the second-order nonlinear dielectric material of the dielectric layer includes a lithium niobate (LiNbO₃). In an embodiment, the second-order nonlinear dielectric material of the dielectric layer includes a second order organic dielectric material. In an embodiment, the dielectric layer includes a non-linear optical material having a non-linear response configured to enhance emissions at the third frequency f_3 . In an embodiment, the plasmonic nanoparticle includes a doubly-resonant plasmonic nanoparticle.

[0033] In an embodiment, the first negative-permittivity layer of the substrate 112 has negative permittivity within a defined frequency range. In an embodiment, the second negative-permittivity layer has negative permittivity within a defined frequency range. In an embodiment, the first negative-permittivity layer of the substrate includes a metallic layer. In an embodiment, the first negative-permittivity layer of the substrate includes a semi-metallic layer. In an embodiment, the first negative-permittivity layer of the substrate includes a semiconductor layer. In an embodiment, the first negative-permittivity layer of the substrate includes a polaritonic dielectric layer.

[0034] In an embodiment of the plasmonic nanoparticle 120.1, the second negative-permittivity layer includes a noble metal. In an embodiment, the second negative-permittivity layer includes a metallic layer. In an embodiment, the second negative-permittivity layer includes a semimetal layer. In an embodiment, the second negative-permittivity layer includes a semiconductor layer or a polaritonic dielectric layer.

[0035] In an embodiment, the dielectric layer 114 has a thickness 115 less than 100 nm. In an embodiment, the dielectric layer is less than 50 nm thick. In an

embodiment, the dielectric layer is less than 25 nm thick. In an embodiment, the dielectric layer is less than 5 nm thick. In an embodiment, the dielectric layer is less than 2.5 nm thick. In an embodiment, the dielectric layer is greater than 5 nm. In an embodiment, the dielectric layer is greater than 5 nm and less than 50 nm thick.

5 [0036] FIG. 1 illustrates an alternative embodiment of the apparatus 105. The apparatus includes the metasurface 110 configured to coherently upconvert light waves emanating from an object and having a first frequency f_1 . The metasurface the substrate 112 has a first negative-permittivity layer comprising a first plasmonic surface. The metasurface includes the plasmonic nanoparticle 120.1 having a base
10 with a second negative-permittivity layer comprising a second plasmonic surface. The metasurface includes the dielectric layer 114 comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface. The metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes
15 including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having the second frequency f_2 , and a third plasmonic resonant mode having the third frequency f_3 . The metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 . The
20 apparatus includes the first light propagation path 132 transmitting the light waves 142 emanating from the object and having the first frequency f_1 to the metasurface. The apparatus includes the pumped laser 152 outputting a monochromatic coherent light 144 having the second frequency f_2 . The apparatus includes the second light propagation path 134 transmitting the monochromatic coherent light having the second
25 frequency f_2 from the pumped laser to the metasurface. The apparatus includes the digital image capture device 116 substantially transparent to light waves having the first frequency f_1 , and configured to (i) capture the generated light waves having the third frequency f_3 and (ii) output a digital image responsive to the light waves emanating from the object. The apparatus includes the third light propagation path
30 136 transmitting the generated light waves having the third frequency f_3 from the metasurface to the digital image capture device.

[0037] FIG. 1 illustrates another alternative embodiment of the apparatus 105. The apparatus includes the metasurface 110 configured to coherently upconvert light waves emanating from an object and having a first frequency f_1 . The metasurface the substrate 112 has a first negative-permittivity layer comprising a first plasmonic surface. The metasurface includes the plasmonic nanoparticle 120.1 having a base with a second negative-permittivity layer comprising a second plasmonic surface. The metasurface includes the dielectric layer 114 comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface. The metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having the second frequency f_2 , and a third plasmonic resonant mode having the third frequency f_3 . The metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 .

[0038] FIG. 3 illustrates an example operational flow 200. After a start operation, the operational flow includes a reception operation 210. The reception operation includes simultaneously receiving in a thin planar metasurface (i) light waves emanating from an object and having a first frequency f_1 and (ii) pumped monochromatic coherent light waves having a second frequency f_2 . In an embodiment, the reception operation may be implemented using the metasurface 110 described in conjunction with FIG. 1. In an embodiment, the first frequency f_1 is a frequency of infrared light waves. A resonant mode mixing operation 220 includes non-linearly combining in the thin planar metasurface the light waves having the first frequency f_1 and the pumped monochromatic coherent light waves having the second frequency f_2 . In an embodiment, the resonant mode mixing operation may be implemented using the substrate 112, the plasmonic nanoparticle 120.1 and the dielectric layer 114 of the metasurface 110 described in conjunction with FIG. 1. A coherent upconversion operation 230 includes generating in the thin planar metasurface by a second order parametric process coherent light waves having a third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 . In an embodiment, the coherent upconversion operation may be implemented using the

substrate 112, the plasmonic nanoparticle 120.1 and the dielectric layer 114 of the metasurface 110 described in conjunction with FIG. 1. A capture operation 240 includes digitizing the generated light waves having the frequency f_3 . In an embodiment, the capture operation may be implemented using the digital image capture device 116 described in conjunction with FIG. 1. A communication operation 250 includes outputting in response to the digitized generated light waves a digital image responsive to the light waves emanating from the object. In an embodiment, the communication operation may be implemented using the digital image capture device 116 described in conjunction with FIG. 1. The operational flow includes an end operation. In an embodiment, the thin planar metasurface includes a thin planar metasurface having a subwavelength thickness relative to f_1 or f_2 . In an embodiment, the operational flow 200 includes blocking light at the second frequency f_2 from reaching the digital image capture device 260.

[0039] FIG. 4 schematically illustrates an example environment 300 in which embodiments may be implemented. The environment includes an apparatus 305 and the object to be imaged 190. In an embodiment, the apparatus has a thickness 311 of less than 10 mm. In an embodiment, the apparatus has a thickness of less than 5 mm. In an embodiment, the apparatus has a thickness of less than 1 mm. In an embodiment, the apparatus has a thickness of less than 0.5 mm. The apparatus 305 includes a metasurface 310 configured to coherently upconvert incident light waves emanating from the object 190 and having a first frequency components $f_{1.1}$ and $f_{1.2}$. The incident light waves are schematically illustrated as light waves 342 and 362 within the apparatus, and as light waves 340 and 360 between the object 190 and the apparatus, which may be light waves in free space. In an embodiment, the first frequency f_1 is a frequency of infrared light waves. In an embodiment, the first frequency f_1 is a frequency of optical light waves. In an embodiment, the light waves emanating from the object include light waves emitted by, reflected from, or transmitted by the object.

[0040] The metasurface 310 includes a substrate 312 having a first negative-permittivity layer comprising a first plasmonic surface. The metasurface includes at least two plasmonic nanoparticles, illustrated by a first plasmonic nanoparticle, schematically illustrated the first nanoparticle 320.1, and a second plasmonic

nanoparticle, schematically illustrated by the second plasmonic nanoparticle 420.1. Each plasmonic nanoparticle has a respective base with a second negative-permittivity layer comprising a respective second plasmonic surface. The metasurface includes a dielectric layer 314 comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the respective second plasmonic surface of each plasmonic nanoparticle of the at least two plasmonic nanoparticles. The dielectric layer has a thickness 315.

[0041] A first portion 372 of the metasurface 310 includes a first plasmonic nanoparticle of the at least two plasmonic nanoparticles, illustrated by the plasmonic nanoparticle 320.1. The first plasmonic nanoparticle is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having a first frequency component $f_{1,1}$, a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency component $f_{3,1}$. The first portion of the metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency component $f_{3,1}$ that is a sum of the first frequency component $f_{1,1}$ and the second frequency f_2 . For example, in an embodiment, if the first frequency component $f_{1,1}$ is 95 THz, if the second frequency component f_2 is 282 THz, the generated third frequency component $f_{3,1}$ will be 377 THz.

[0042] A second portion 472 of the metasurface 310 includes a second plasmonic nanoparticle of the at least two plasmonic nanoparticles, illustrated by the plasmonic nanoparticle 420.1. The second plasmonic nanoparticle is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency component $f_{1,2}$, a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency component $f_{3,2}$. The second portion of the metasurface is further configured to generate by the second order parametric process coherent light waves having the third frequency component $f_{3,2}$ that is a sum of the first frequency component $f_{1,2}$ and the second frequency f_2 . For example, in an embodiment, if the first frequency component $f_{1,2}$ is 100 THz, if the second frequency component f_2 is 282 THz, the

generated third frequency component $f_{3.1}$ will be 387 THz. The metasurface includes a second light propagation path 334 from a source 352 of pumped monochromatic coherent light waves having the second frequency f_2 to the metasurface. The apparatus 305 includes a digital image capture device 316 substantially transparent to light waves having the first frequency components $f_{1.1}$ and $f_{1.2}$, and configured to separately capture the light waves having the third frequency components $f_{3.1}$ and $f_{3.2}$.

[0043] FIG. 5 schematically illustrates a top view of an embodiment of the first plasmonic nanoparticle, illustrated by the plasmonic nanoparticle 320.1, and the second plasmonic nanoparticle, illustrated by the plasmonic nanoparticle 420.1. In an embodiment, the first plasmonic nanoparticle includes a base having (i) a first characteristic 322 that in combination with the dielectric layer 314 establishes first spatial modes 323.1 and 323.2 at the frequency $f_{1.1}$ and (ii) a second characteristic 324 that establishes second spatial modes 325.1 and 325.2 at frequency f_2 . The first spatial mode and the second spatial mode spatially overlapping each other in the dielectric layer and creating third plasmonic resonant modes 328.1-328.4 having the third frequency f_3 . In an embodiment, the base of the first plasmonic nanoparticle has a first dimension characteristic 322, such as a length, that in combination with the dielectric layer 314 establishes a first gap-plasmon guided mode. In an embodiment, the first side dimension characteristic 322 includes a length that is much greater than a thickness of the dielectric layer 315. For example, in an embodiment, “much greater” means the first side dimension is at least five times greater than the thickness of the dielectric layer.

[0044] In an embodiment, the second plasmonic nanoparticle 420.1 includes a base having (i) a first characteristic 422 that in combination with the dielectric layer 314 establishes first spatial modes 423.1 and 423.2 at the frequency $f_{1.2}$ and (ii) a second characteristic 424 that in combination with the dielectric layer establishes second spatial modes 425.1 and 425.2 at the frequency f_2 . The first spatial modes and the second spatial modes spatially overlapping each other in the dielectric layer and creating the third plasmonic resonant modes 428.1-428.4 having the third frequency f_3 . In an embodiment, the base of the second plasmonic nanoparticle has a first dimension characteristic 422, such as a length, that in combination with the dielectric layer establishes a second gap-plasmon guided mode. In an embodiment, the first side

dimension characteristic 422 includes a length that is much greater than the thickness of the dielectric layer 315. The schematic illustrations of the plasmonic resonance modes may or may not be representative of actual the plasmonic resonance modes.

[0045] Returning to FIG. 4, in an embodiment, the digital image capture device 316 includes a Foveon X3 array of layered pixel sensors responsive to the third frequency components $f_{3.1}$ and $f_{3.2}$. In an embodiment, the digital image capture device includes a Bayer filter pattern including interlaced grids responsive to the third frequency components $f_{3.1}$ and $f_{3.2}$. In an embodiment, the digital image capture device includes a CCD based separator responsive to the third frequency components $f_{3.1}$ and $f_{3.2}$. In an embodiment, the digital image capture device is further configured to output an image responsive to the light waves emanating from the object at the first frequency components $f_{1.1}$ and $f_{1.2}$. In an embodiment, the digital image capture device is further configured to output a digital image responsive to the light waves emanating from the object at the first frequency components $f_{1.1}$ and $f_{1.2}$.

[0046] In an embodiment, the apparatus 305 includes a first light propagation path 332 transmitting the light waves 342 and 362 emanating from the object 190 and having the first frequency components $f_{1.1}$ and $f_{1.2}$ to the metasurface 310. In an embodiment, the apparatus 305 includes a third light propagation path 336 transmitting the generated light waves 346 and 362 having the third frequency components $f_{3.1}$ and $f_{3.2}$ from the metasurface to the digital image capture device 316. In an embodiment, the apparatus includes a band block filter 318 configured to block light at the second frequency f_2 and interposed in the third light propagation path between the metasurface and the digital image capture device. In an embodiment, the third light propagation path includes at least a portion of a first light propagation path directing the light waves emanating from the object toward the metasurface. In an embodiment, the apparatus includes a source 352 of the pumped monochromatic coherent light waves having the second frequency f_2 and optically coupled with the second light propagation path 334. In an embodiment, the source includes a pumped laser outputting the pumped monochromatic coherent light waves having the second frequency f_2 . In an embodiment, the apparatus includes a lens 354 configured to focus the light waves 340 and 360 emanating from the object 190 and having the first frequency components $f_{1.1}$ and $f_{1.2}$ onto the metasurface.

[0047] In an embodiment of the apparatus 305, the first portion 372 of the metasurface 310 includes at least two first plasmonic nanoparticles, illustrated as first plasmonic nanoparticles 320.1 and 320.2. In an embodiment, the second portion 472 of the metasurface includes at least two second plasmonic nanoparticles, illustrated as second plasmonic nanoparticles 420.1 and 420.2.

[0048] FIG. 6 illustrates an example operational flow 500. After a start operation, the operational flow includes a reception operation 510. The reception operation includes simultaneously receiving (i) light waves emanating from an object and having first frequency components $f_{1.1}$ and $f_{1.2}$, and (ii) pumped monochromatic coherent light waves having a second frequency f_2 . In an embodiment, the first frequency components $f_{1.1}$ and $f_{1.2}$ are frequencies of light waves. In an embodiment, the reception operation may be implemented using the metasurface 310 described in conjunction with FIG. 4. A first resonant mixing operation 520 includes non-linearly combining the light waves having the first frequency component $f_{1.1}$ and the pumped monochromatic coherent light waves having the second frequency f_2 . In an embodiment, the first resonant mixing operation may be implemented using the first portion 372 of the metasurface 310 described in conjunction with FIG. 4, including the plasmonic nanoparticle 320.1, the substrate 312, and the dielectric 314. A first coherent upconversion operation 530 includes generating by a second order parametric process coherent light waves having a third frequency component $f_{3.1}$ that is a sum of the first frequency $f_{1.1}$ and the frequency and the second frequency f_2 . In an embodiment, the first coherent upconversion operation may be implemented using the first portion 372 of the metasurface 310 described in conjunction with FIG. 4, including the plasmonic nanoparticle 320.1, the substrate 312, and the dielectric 314. A second resonant mixing operation 540 includes non-linearly combining the light waves having the first frequency component $f_{1.2}$ and the pumped monochromatic coherent light waves having the second frequency f_2 . In an embodiment, the second resonant mixing operation may be implemented using the second portion 472 of the metasurface 310, including the plasmonic nanoparticle 420.1, the substrate 312, and the dielectric 314. A second coherent upconversion operation 550 includes generating by a second order parametric process coherent light waves having a third frequency component $f_{3.2}$ that is a sum of the first frequency $f_{1.2}$ and the second frequency f_2 . In

an embodiment, the second coherent upconversion operation may be implemented using the second portion 372 of the metasurface 310 described in conjunction with FIG. 4, including the plasmonic nanoparticle 420.1, the substrate 312, and the dielectric 314. A capture operation 560 includes digitizing the generated light waves having the frequency components $f_{3.1}$ and $f_{3.2}$. In an embodiment, the digitizing operation may be implemented using the digital image capture device 316 described in conjunction with FIG. 4. A communication operation 570 includes outputting in response to the digitized generated light waves a digital image responsive to the light waves having the frequency components $f_{1.1}$ and $f_{1.2}$ emanating from the object. In an embodiment, the communication operation may be implemented using the digital image capture device 316 described in conjunction with FIG. 4. The operational flow includes an end operation.

[0049] In an embodiment, the operational flow 500 includes blocking light at the second frequency f_2 from being digitized by the capture operation. In an embodiment, the operational flow includes focusing the light waves emanating from an object and having first frequency components $f_{1.1}$ and $f_{1.2}$.

[0050] FIG. 7 illustrates an environment 600 that includes the object 190 and an apparatus 605. The apparatus includes a metasurface 610 configured to coherently upconvert incident light waves emanating from the object 190 and respectively having first frequency components $f_{1.1}$ and $f_{1.2}$. The light waves as schematically illustrated as light waves 642 and 762 within the apparatus, and as light waves 640 and 760 between the object and the apparatus. In an embodiment, the first frequency components $f_{1.1}$ and $f_{1.2}$ are frequencies of infrared light waves. In an embodiment, the metasurface includes a substrate 612 having a first negative-permittivity layer comprising a substrate plasmonic surface. The metasurface includes a first metasurface pixel 672 comprising a first plasmonic nanoparticle 620.1 having a base with a negative-permittivity layer comprising a first pixel plasmonic surface. The metasurface includes a second metasurface pixel 772 comprising a second plasmonic nanoparticle 720.1 having a second base with a second negative-permittivity layer comprising a second pixel plasmonic surface. The metasurface includes a dielectric layer 614 comprising a second-order nonlinear dielectric material disposed between the substrate plasmonic surface and the respective first pixel plasmonic surface and the

second pixel plasmonic surface. The dielectric layer has a thickness 615. The first metasurface pixel is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency component $f_{1.1}$, a second

5 plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency component $f_{3.1}$. The second metasurface pixel is configured to form at least three plasmonic resonant modes in the dielectric layer. The at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency component $f_{1.2}$, a second plasmonic resonant mode having

10 the second frequency f_2 , and the third plasmonic resonant mode having a third frequency component $f_{3.2}$. The metasurface is configured to generate by a second order parametric process coherent light waves having the third frequency components $f_{3.1}$ and $f_{3.2}$ that are a sum of the first frequency components $f_{1.1}$ and $f_{1.2}$ and the second frequency f_2 respectively. The apparatus includes a second light propagation

15 path from a source 652 of pumped monochromatic coherent light waves 644 having the second frequency f_2 to the metasurface. The second light propagation path is illustrated by the second light propagation path 334 described in conjunction with FIG. 4. The apparatus includes a digital image capture device 616 substantially transparent to light waves having the first frequency components $f_{1.1}$ and $f_{1.2}$. The digital image

20 capture device includes a first capture pixel 674 configured to capture the light 646 having the third frequency component $f_{3.1}$ generated by the first metasurface pixel 672. The digital image capture device includes a second capture pixel 774 configured to capture the light 766 having the third frequency component $f_{3.2}$ generated by the second metasurface pixel. For example, in an embodiment, the digital image capture

25 device may be configured to capture a color separated image, or a frequency separated image. In an embodiment, the apparatus has a thickness of less than 10 mm. In an embodiment, the apparatus has a thickness of less than 5 mm. In an embodiment, the apparatus has a thickness of less than 1 mm. In an embodiment, the apparatus has a thickness of less than 0.5 mm.

30 [0051] In an embodiment, the digital image capture device 616 includes a first capture pixel 674 configured and aligned to directly capture the light 646 having the third frequency component $f_{3.1}$ and a second capture pixel 774 configured and aligned

to capture 766 light having the third frequency component $f_{3,2}$. In an embodiment, the digital image capture device is further configured to output an image responsive to the light waves emanating from the object 190 at the first frequency components $f_{1,1}$ and $f_{1,2}$. In an embodiment, the digital image generator is configured to output a digital image responsive to the light waves emanating from the object.

[0052] In an embodiment, the first metasurface pixel 672 includes at least two first plasmonic nanoparticles, illustrated by first plasmonic nanoparticles 620.1 and 620.2. Each first plasmonic nanoparticle having a respective base with a negative-permittivity layer comprising a portion the first pixel plasmonic surface. In an embodiment, the second metasurface pixel 772 includes at least two second plasmonic nanoparticles, illustrated by second plasmonic nanoparticles 720.1 and 720.2. Each second plasmonic nanoparticle having a respective base with a negative-permittivity layer comprising a portion the second pixel plasmonic surface.

[0053] In an embodiment, the apparatus 605 includes a first light propagation path transmitting the light waves emanating from the object 190 having the first frequency components $f_{1,1}$ and $f_{1,2}$ to the metasurface 610. The first light propagation path is illustrated by the first light propagation path 322 described in conjunction with FIG. 4. In an embodiment, the apparatus includes a third light propagation path transmitting the generated light waves having the third frequency components $f_{3,1}$ and $f_{3,2}$ from the metasurface to the digital image capture device. The third light propagation path is illustrated by the third light propagation path 336 described in conjunction with FIG. 4. In an embodiment, the apparatus includes a band block filter configured to block light at the second frequency f_2 and interposed in the third light propagation path between the metasurface and the digital image capture device. The band block filter is illustrated by the band block filter 318 described in conjunction with FIG. 4. In an embodiment, the apparatus includes a lens 774. In an embodiment, the lens 774 is similar to the lens 354 described in conjunction with FIG. 4.

[0054] FIG. 8 illustrates an example operational flow 800. After a start operation, the operational flow includes a reception operation 810. The reception operation includes simultaneously receiving (i) light waves emanating from an object and having first frequency components $f_{1,1}$ and $f_{1,2}$, and (ii) pumped monochromatic coherent light waves having a second frequency f_2 . In an embodiment, the reception

operation may be implemented using the metasurface 610 described in conjunction with FIG. 7. A first resonant mode mixing operation 820 includes non-linearly combining the light waves having the first frequency component $f_{1,1}$ and the pumped monochromatic coherent light waves having the second frequency f_2 . In an embodiment, the first resonant mode mixing operation may be implemented using the first metasurface pixel 672 of the metasurface 610 described in conjunction with FIG. 7. A first coherent upconversion operation 830 includes generating by a second order parametric process coherent light waves having a third frequency component $f_{3,1}$ that is a sum of the first frequency component $f_{1,1}$ and the frequency of the second frequency f_2 . In an embodiment, the first coherent upconversion operation may be implemented in the first metasurface pixel 672 of the metasurface 610 described in conjunction with FIG. 7. A second resonant mode mixing operation 840 includes non-linearly combining the light waves having the first frequency component $f_{1,2}$ and the pumped monochromatic coherent light waves having the second frequency f_2 . In an embodiment, the second resonant mode mixing operation may be implemented using the second pixel 772 of the metasurface 610 described in conjunction with FIG. 7. A second coherent upconversion operation 850 includes generating by a second order parametric process coherent light waves having a third frequency component $f_{3,2}$ that is a sum of the first frequency $f_{1,2}$ and the second frequency f_2 . In an embodiment, the second coherent upconversion operation may be implemented in the second metasurface pixel 772 of the metasurface 610 described in conjunction with FIG. 7. A first imaging operation 860 includes capturing the generated light waves having the third frequency component $f_{3,1}$. In an embodiment, the first imaging operation may be implemented using the first capture pixel 674 of the digital image capture device 616 described in conjunction with FIG. 7. A second imaging operation 870 includes capturing the generated light waves having the third frequency component $f_{3,2}$. In an embodiment, the second imaging operation may be implemented using the second capture pixel 774 of the digital image capture device 616 described in conjunction with FIG. 7. A conversion operation 880 includes digitizing the captured light waves having the third frequency component $f_{3,1}$ and the captured light waves having the third frequency $f_{3,2}$. In an embodiment, the conversion operation may be implemented using the digital image capture device 616 described in conjunction with FIG. 7. A communication operation 890 includes outputting in response to the digitized captured

light waves an image responsive to the light waves frequency components $f_{1.1}$ and $f_{1.2}$ emanating from the object. In an embodiment, the communication operation may be implemented using the digital image capture device 616 described in conjunction with FIG. 7. The operational flow includes an end operation.

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[0055] All references cited herein are hereby incorporated by reference in their entirety or to the extent their subject matter is not otherwise inconsistent herewith.

[0056] In some embodiments, “configured” or “configured to” includes at least one of designed, set up, shaped, implemented, constructed, or adapted for at least one of a particular purpose, application, or function. In some embodiments, “configured” or “configured to” includes positioned, oriented, or structured for at least one of a particular purpose, application, or function.

[0057] It will be understood that, in general, terms used herein, and especially in the appended claims, are generally intended as “open” terms. For example, the term “including” should be interpreted as “including but not limited to.” For example, the term “having” should be interpreted as “having at least.” For example, the term “has” should be interpreted as “having at least.” For example, the term “includes” should be interpreted as “includes but is not limited to,” etc. It will be further understood that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of introductory phrases such as “at least one” or “one or more” to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles “a” or “an” limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases “one or more” or “at least one” and indefinite articles such as “a” or “an” (e.g., “a receiver” should typically be interpreted to mean “at least one receiver”); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, it will be recognized that such recitation should typically be interpreted to mean *at least* the recited number (e.g., the bare recitation of “at least two

chambers,” or “a plurality of chambers,” without other modifiers, typically means *at least* two chambers).

- [0058] In those instances where a phrase such as “at least one of A, B, and C,” “at least one of A, B, or C,” or “an [item] selected from the group consisting of A, B, and C,” is used, in general such a construction is intended to be disjunctive (*e.g.*, any of these phrases would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, or A, B, and C together, and may further include more than one of A, B, or C, such as A₁, A₂, and C together, A, B₁, B₂, C₁, and C₂ together, or B₁ and B₂ together). It will be further understood that virtually any disjunctive word or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase “A or B” will be understood to include the possibilities of “A” or “B” or “A and B.”
- [0059] The herein described aspects depict different components contained within, or connected with, different other components. It is to be understood that such depicted architectures are merely examples, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively “associated” such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as “associated with” each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being “operably connected,” or “operably coupled,” to each other to achieve the desired functionality. Any two components capable of being so associated can also be viewed as being “operably couplable” to each other to achieve the desired functionality. Specific examples of operably couplable include but are not limited to physically mateable or physically interacting components or wirelessly interactable or wirelessly interacting components.
- [0060] Aspects of the subject matter described herein are set out in the following numbered clauses:

1. An apparatus comprising:

a metasurface configured to coherently upconvert incident light waves emanating from an object and having a first frequency f_1 , the metasurface comprising:

5 a substrate having a first negative-permittivity layer comprising a first plasmonic surface;

a plasmonic nanoparticle having a base with a second negative-permittivity layer comprising a second plasmonic surface;

10 a dielectric layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface;

wherein the metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 ; and

wherein the metasurface is further configured to generate by a second order parametric process coherent light having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 ; and

20 a second light propagation path from a source of pumped monochromatic coherent light waves having the second frequency f_2 to the metasurface; and

a digital image capture device substantially transparent to light waves having the first frequency f_1 and configured to capture the generated light waves having the frequency f_3 .

25 2. The apparatus of clause 1, further comprising:

a first light propagation path transmitting the light waves emanating from the object and having the first frequency f_1 to the metasurface.

3. The apparatus of clause 1, further comprising:

30 a third light propagation path transmitting the generated light waves having the third frequency f_3 from the metasurface to the digital image capture device.

4. The apparatus of clause 3, further comprising:

a band block filter configured to block light at the second frequency f_2 and interposed in the third light propagation path between the metasurface and the digital image capture device.

5. The apparatus of clause 3, wherein the third light propagation path includes at least a portion of a first light propagation path transmitting the light waves emanating from the object toward the metasurface.
6. The apparatus of clause 1, further comprising:
 - a source of pumped monochromatic coherent light waves having the second frequency f_2 and optically coupled with the second light propagation path.
7. The apparatus of clause 6, wherein the source includes a pumped laser outputting the pumped monochromatic coherent light waves having the second frequency f_2 .
8. The apparatus of clause 1, further comprising:
 - a lens configured to focus the light waves emanating from the object onto the metasurface.
9. The apparatus of clause 8, wherein the lens includes a flat lens.
10. The apparatus of clause 8, wherein the lens includes a metamaterial lens.
11. The apparatus of clause 8, wherein the lens includes a bulk optics lens.
12. The apparatus of clause 1, wherein the first plasmonic resonant mode frequency f_1 is spectrally separated from the second plasmonic resonant mode frequency f_2 .
13. The apparatus of clause 1, wherein the first plasmonic resonant mode frequency f_1 is a function of a first characteristic of the plasmonic nanoparticle, the second plasmonic resonant mode frequency f_2 is a function of a second characteristic of the plasmonic nanoparticle, and the third plasmonic resonant mode frequency f_3 is a function of both the first characteristic of the plasmonic nanoparticle and the second characteristic of the plasmonic nanoparticle.
14. The apparatus of clause 13, wherein the first characteristic of the plasmonic nanoparticle includes a first structural characteristic of the plasmonic nanoparticle and the second characteristic of the plasmonic nanoparticle includes a second structural characteristic of the plasmonic nanoparticle.
15. The apparatus of clause 13, wherein the first characteristic of the plasmonic nanoparticle includes a first dimensional characteristic of the plasmonic nanoparticle and the second characteristic of the plasmonic nanoparticle includes a second dimensional characteristic of the plasmonic nanoparticle.

16. The apparatus of clause 1, wherein the first plasmonic resonant mode frequency f_1 is a function of a first side dimension of a non-square rectangular base of the plasmonic nanoparticle, the second plasmonic resonant mode frequency f_2 is a function of a second side dimension of the non-square rectangular base of the plasmonic nanoparticle, and the
5 third plasmonic resonant mode frequency f_3 is a function of both the first side dimension of the non-square rectangular base of the plasmonic nanoparticle and the second side dimension of the non-square rectangular base of the plasmonic nanoparticle.
17. The apparatus of clause 1, wherein the plasmonic nanoparticle includes a base having (i) a first characteristic that establishes a first spatial mode at the first plasmonic
10 resonant mode frequency f_1 and (ii) a second characteristic that establishes a second spatial mode at the second plasmonic resonant mode frequency f_2 , the first spatial mode and the second spatial mode overlapping each other in the dielectric layer and creating the third plasmonic resonant mode having the third frequency f_3 .
18. The apparatus of clause 17, wherein the plasmonic nanoparticle includes a non-
15 square rectangular base having (i) a first dimension characteristic that establishes a first spatial mode at the first plasmonic resonant mode frequency f_1 and (ii) a second dimension characteristic that establishes a second spatial mode at the second plasmonic resonant mode frequency f_2 , the first spatial mode and the second spatial mode spatially overlapping each other in the dielectric layer and creating the third plasmonic resonant
20 mode having the third frequency f_3 .
19. The apparatus of clause 17, wherein the base of the plasmonic nanoparticle includes a first dimension characteristic that in combination with the dielectric layer establishes a first gap-plasmon guided mode.
20. The apparatus of clause 17, wherein the base of the plasmonic nanoparticle
25 includes a second dimension characteristic that in combination with the dielectric layer establishes a second gap-plasmon guided mode.
21. The apparatus of clause 1, wherein the first plasmonic resonant mode frequency f_1 and the second plasmonic resonant mode frequency f_2 are a function of the second-order nonlinear dielectric material disposed between the first plasmonic surface of the substrate
30 and the second plasmonic surface of the plasmonic nanoparticle.
22. The apparatus of clause 1, wherein the digital image capture device is further configured to output an image responsive to the light waves emanating from the object.
23. The apparatus of clause 1, wherein the metasurface includes:

a substrate having a first negative-permittivity layer comprising a first plasmonic surface;

at least two plasmonic nanoparticles, each plasmonic nanoparticle of the at least two plasmonic nanoparticles having a respective base with a second negative-permittivity layer comprising a second plasmonic surface;

the dielectric layer including a second-order nonlinear material disposed between the first plasmonic surface and the respective second plasmonic surface of each of the at least two plasmonic nanoparticles; and

wherein the metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 ; and

wherein the metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 .

24. The apparatus of clause 1, wherein both the substrate and the base of the plasmonic nanoparticle have a parallel planar geometry.

25. The apparatus of clause 1, wherein the metasurface includes a planar metasurface.

26. The apparatus of clause 1, wherein the metasurface includes a flat panel metasurface.

27. The apparatus of clause 26, wherein the flat panel metasurface includes a curved flat panel metasurface.

28. The apparatus of clause 1, wherein the metasurface includes a metasurface formed on a silicon chip.

29. The apparatus of clause 1, wherein the metasurface includes a metasurface on a chip integrated platform.

30. The apparatus of clause 1, wherein the apparatus includes a planar apparatus.

31. The apparatus of clause 1, wherein the apparatus includes a flat panel apparatus.

32. The apparatus of clause 1, wherein the apparatus is formed on a silicon chip.

33. The apparatus of clause 1, wherein the apparatus is formed on a CMOS chip.

34. The apparatus of clause 1, wherein the apparatus includes on a chip integrated platform.

35. The apparatus of clause 1, wherein the metasurface includes an optically thin metasurface.
36. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle is substantially conformal to the first plasmonic surface.
- 5 37. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle is substantially planar.
38. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle has a major side and a minor side shorter than the major side.
39. The apparatus of clause 38, wherein the major side corresponds to a base
10 dimension in a first direction and the minor side corresponds to a shorter base dimension in a non-aligned direction.
40. The apparatus of clause 39, wherein the non-aligned direction is at least substantially perpendicular to the first direction.
41. The apparatus of clause 1, wherein the plasmonic nanoparticle includes at least two
15 joined or proximate plasmonic nanoparticles forming the base with a second negative-permittivity layer comprising the second plasmonic surface.
42. The apparatus of clause 41, wherein the at least two joined or proximate plasmonic nanoparticles form a non-square rectangular base with a second negative-permittivity layer comprising a second plasmonic surface.
- 20 43. The apparatus of clause 1, wherein the plasmonic nanoparticle includes a nanorod having a non-square rectangular base with the second negative-permittivity layer.
44. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle includes at least one of a rectangular, an ellipsoidal, or a triangular shaped base.
45. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle has an
25 elongated shaped base.
46. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle has an arbitrary shaped base.
47. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle has a major side length between about 1000 and about 5000 nm.
- 30 48. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle has a major side length between about 1500 and about 4000 nm.
49. The apparatus of clause 1, wherein the base of the plasmonic nanoparticle has a minor side length between about 500 and about 2000 nm.

50. The apparatus of clause 1, wherein the dielectric layer includes a dielectric layer region.
51. The apparatus of clause 1, wherein the dielectric layer includes a dielectric filled gap.
- 5 52. The apparatus of clause 1, wherein the second-order nonlinear dielectric material of the dielectric layer includes a potassium titanyl phosphate (KTP).
53. The apparatus of clause 1, wherein the second-order nonlinear dielectric material of the dielectric layer includes a lithium niobate (LiNbO₃).
54. The apparatus of clause 1, wherein the second-order nonlinear dielectric material
10 of the dielectric layer includes a second order organic dielectric material.
55. The apparatus of clause 1, wherein the dielectric layer includes a non-linear optical material having a non-linear response configured to enhance emissions at the third frequency f_3 .
56. The apparatus of clause 1, wherein the plasmonic nanoparticle includes a doubly-
15 resonant plasmonic nanoparticle.
57. The apparatus of clause 1, wherein the first negative-permittivity layer of the substrate has negative permittivity within a defined frequency range.
58. The apparatus of clause 1, wherein the second negative-permittivity layer has negative permittivity within a defined frequency range.
- 20 59. The apparatus of clause 1, wherein the first negative-permittivity layer includes a metallic layer.
60. The apparatus of clause 1, wherein the first negative-permittivity layer includes a semi-metallic layer.
61. The apparatus of clause 1, wherein the first negative-permittivity layer includes a
25 semiconductor layer.
62. The apparatus of clause 1, wherein the first negative-permittivity layer includes a polaritonic dielectric layer.
63. The apparatus of clause 1, wherein the second negative-permittivity layer includes a noble metal.
- 30 64. The apparatus of clause 1, wherein the second negative-permittivity layer includes a metallic layer.
65. The apparatus of clause 1, wherein the second negative-permittivity layer includes a semimetal layer.

66. The apparatus of clause 1, wherein the second negative-permittivity layer includes a semiconductor layer or a polaritonic dielectric layer.
67. The apparatus of clause 1, wherein the dielectric layer is less than 100 nm thick.
68. The apparatus of clause 1, wherein the dielectric layer is less than 50 nm thick.
- 5 69. The apparatus of clause 1, wherein the dielectric layer is less than 25 nm thick.
70. The apparatus of clause 1, wherein the dielectric layer is less than 5 nm thick.
71. The apparatus of clause 1, wherein the dielectric layer is less than 2.5 nm thick.
72. The apparatus of clause 1, wherein the dielectric layer is greater than 5 nm.
73. The apparatus of clause 1, wherein the dielectric layer is greater than 5 nm and less
10 than 50 nm thick.
74. An apparatus comprising:
 a metasurface configured to coherently upconvert light waves emanating from
 an object and having a first frequency f_1 , the metasurface comprising:
 a substrate having a first negative-permittivity layer comprising a first
 15 plasmonic surface;
 a plasmonic nanoparticle having a base with a second negative-
 permittivity layer comprising a second plasmonic surface;
 a dielectric layer comprising a second-order nonlinear dielectric
 material disposed between the first plasmonic surface and the second
 20 plasmonic surface;
 wherein the metasurface is configured to form at least three plasmonic
 resonant modes in the dielectric layer, the at least three plasmonic resonant
 modes including a first plasmonic resonant mode having the first frequency f_1 ,
 a second plasmonic resonant mode having a second frequency f_2 , and a third
 25 plasmonic resonant mode having a third frequency f_3 ; and
 wherein the metasurface is further configured to generate by a second
 order parametric process coherent light waves having the third frequency f_3
 that is a sum of first frequency f_1 and the second frequency f_2 ;
 a first light propagation path transmitting the light waves emanating from
 30 the object and having the first frequency f_1 to the metasurface;
 a pumped laser outputting a monochromatic coherent light having the
 second frequency f_2 ;

a second light propagation path transmitting monochromatic coherent light having the second frequency f_2 from the pumped laser to the metasurface;

a digital image capture device substantially transparent to the light waves having the first frequency f_1 , and configured to (i) capture the generated light waves having the third frequency f_3 and (ii) output an image responsive to the light waves emanating from the object; and

a third light propagation path transmitting the generated light waves having the third frequency f_3 from the metasurface to the digital image capture device.

75. A method comprising:

simultaneously receiving in a thin planar metasurface (i) light waves emanating from an object and having a first frequency f_1 and (ii) pumped monochromatic coherent light waves having a second frequency f_2 ;

non-linearly combining in the thin planar metasurface the light waves having the first frequency f_1 and the pumped monochromatic coherent light waves having the second frequency f_2 ;

generating in the thin planar metasurface by a second order parametric process coherent light waves having a third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 ;

digitizing the generated light waves having the frequency f_3 ; and

outputting in response to the digitized generated light waves a digital image responsive to the light waves emanating from the object.

76. The method of clause 75, wherein the thin planar metasurface includes a thin planar metasurface having a subwavelength thickness relative to f_1 or f_2 .

77. The method of clause 75, further comprising:

blocking light waves at the second frequency f_2 from reaching the digital image capture device.

78. A metasurface configured to coherently upconvert incident light waves having a first frequency f_1 , the metasurface comprising:

a substrate having a first negative-permittivity layer comprising a first plasmonic surface;

a plasmonic nanoparticle having a base with a second negative-permittivity layer comprising a second plasmonic surface;

a dielectric layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface;

wherein the metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 ; and

wherein the metasurface is further configured to generate by a second order parametric process coherent light having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 .

79. An apparatus comprising:

a metasurface configured to coherently upconvert incident light waves emanating from an object and having first frequency components $f_{1,1}$ and $f_{1,2}$, the metasurface comprising:

a substrate having a first negative-permittivity layer comprising a first plasmonic surface;

at least two plasmonic nanoparticles, each having a respective base with a second negative-permittivity layer comprising a respective second plasmonic surface;

a dielectric layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the respective second plasmonic surface of each plasmonic nanoparticle of the at least two plasmonic nanoparticles;

wherein a first portion of the metasurface includes a first plasmonic nanoparticle of the at least two plasmonic nanoparticles configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency component $f_{1,1}$, a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency component $f_{3,1}$;

wherein the first portion of the metasurface is further configured to generate by a second order parametric process coherent light waves having

the third frequency component $f_{3,1}$ that is a sum of the first frequency component $f_{1,1}$ and the second frequency f_2 ;

wherein a second portion of the metasurface includes a second plasmonic nanoparticle of the at least two plasmonic nanoparticles configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency component $f_{1,2}$, a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency component $f_{3,2}$;

wherein the second portion of the metasurface is further configured to generate by the second order parametric process coherent light waves having the third frequency component $f_{3,2}$ that is a sum of the first frequency component $f_{1,2}$ and the second frequency f_2 ; and

a second light propagation path from a source of pumped monochromatic coherent light waves having the second frequency f_2 to the metasurface; and a digital image capture device substantially transparent to light waves having the first frequency components $f_{1,1}$ and $f_{1,2}$ and configured to separately capture the light waves having the third frequency components $f_{3,1}$ and $f_{3,2}$.

80. The apparatus of clause 79, wherein the first plasmonic nanoparticle includes a base having (i) a first characteristic that establishes a first spatial mode at the frequency $f_{1,1}$ and (ii) a second characteristic that establishes a second spatial mode at frequency f_2 , the first spatial mode and the second spatial mode spatially overlapping each other in the dielectric layer and creating the third plasmonic resonant mode having the third frequency f_3 .

81. The apparatus of clause 79, wherein the base of the first plasmonic nanoparticle has a first dimension characteristic that in combination with the dielectric layer establishes a first gap-plasmon guided mode.

82. The apparatus of clause 79, wherein the second plasmonic nanoparticle includes a base having (i) a first characteristic that establishes a first spatial mode at the frequency $f_{1,2}$ and (ii) a second characteristic that establishes a second spatial mode at the frequency f_2 , the first spatial mode and the second spatial mode spatially overlapping each other in the dielectric layer and creating the third plasmonic resonant mode having the third frequency f_3 .

83. The apparatus of clause 79, wherein the base of the second plasmonic nanoparticle has a first dimension characteristic that in combination with the dielectric layer establishes a second gap-plasmon guided mode.
84. The apparatus of clause 79, wherein the digital image capture device includes a
5 Foveon X3 array of layered pixel sensors responsive to the third frequency components $f_{3.1}$ and $f_{3.2}$.
85. The apparatus of clause 79, wherein the digital image capture device includes a Bayer filter pattern including interlaced grids responsive to the third frequency components $f_{3.1}$ and $f_{3.2}$.
- 10 86. The apparatus of clause 79, wherein the digital image capture device includes a CCD based separator responsive to the third frequency components $f_{3.1}$ and $f_{3.2}$.
87. The apparatus of clause 79, wherein the digital image capture device is further configured to output an image responsive to the light waves emanating from the object at the first frequency components $f_{1.1}$ and $f_{1.2}$.
- 15 88. The apparatus of clause 79, further comprising:
a first light propagation path transmitting the light waves emanating from the object and having the first frequency components $f_{1.1}$ and $f_{1.2}$ to the metasurface.
89. The apparatus of clause 79, further comprising:
20 a third light propagation path transmitting the generated light waves having the third frequency components $f_{3.1}$ and $f_{3.2}$ from the metasurface to the digital image capture device.
90. The apparatus of clause 11, further comprising:
a band block filter configured to block light at the second frequency f_2 and
25 interposed in the third light propagation path between the metasurface and the digital image capture device.
91. The apparatus of clause 11, wherein the third light propagation path includes at least a portion of a first light propagation path directing the light waves emanating from the object toward the metasurface.
- 30 92. The apparatus of clause 79, further comprising:
a source of pumped monochromatic coherent light waves having the second frequency f_2 and optically coupled with the second light propagation path.

93. The apparatus of clause 14, wherein the source includes a pumped laser outputting the pumped monochromatic coherent light waves having the second frequency f_2 .
94. The apparatus of clause 79, further comprising:
a lens configured to focus the light waves emanating from the object and
5 having the first frequency components $f_{1.1}$ and $f_{1.2}$ onto the metasurface.
95. The apparatus of clause 79, wherein the first portion of the metasurface includes at least two first plasmonic nanoparticles.
96. The apparatus of clause 79, wherein the second portion of the metasurface includes at least two second plasmonic nanoparticles.
- 10 97. A method comprising:
simultaneously receiving (i) light waves emanating from an object and having first frequency components $f_{1.1}$ and $f_{1.2}$, and (ii) pumped monochromatic coherent light waves having a second frequency f_2 ;
non-linearly combining the light waves having the first frequency component $f_{1.1}$
15 and the pumped monochromatic coherent light waves having the second frequency f_2 ;
generating by a second order parametric process coherent light waves having a third frequency component $f_{3.1}$ that is a sum of the first frequency $f_{1.1}$ and the second frequency f_2 ;
non-linearly combining the light waves having the first frequency component $f_{1.2}$
20 and the pumped monochromatic coherent light waves having the second frequency f_2 ;
generating by a second order parametric process coherent light waves having a third frequency component $f_{3.2}$ that is a sum of the first frequency $f_{1.2}$ and the second frequency f_2 ;
digitizing the generated light waves having the frequency components $f_{3.1}$ and $f_{3.2}$;
25 and
outputting in response to the digitized generated light waves an image responsive to the light waves having frequency components $f_{1.1}$ and $f_{1.2}$ emanating from the object.
98. The method of clause 97, further comprising:
blocking light at the second frequency f_2 from being digitized.
- 30 99. The method of clause 97, further comprising:
focusing the light waves emanating from the object and having first frequency components $f_{1.1}$ and $f_{1.2}$.
100. An apparatus comprising:

a metasurface configured to coherently upconvert incident light waves emanating from an object and having first frequency components $f_{1.1}$ and $f_{1.2}$, the metasurface comprising:

5 a substrate having a first negative-permittivity layer comprising a substrate plasmonic surface;

a first metasurface pixel comprising a first plasmonic nanoparticle having a base with a negative-permittivity layer comprising a first pixel plasmonic surface;

10 a second metasurface pixel comprising a second plasmonic nanoparticle having a second base with a second negative-permittivity layer comprising a second pixel plasmonic surface;

a dielectric layer comprising a second-order nonlinear dielectric material disposed between the substrate plasmonic surface and the respective first pixel plasmonic surface and the second pixel plasmonic surface;

15 wherein the first metasurface pixel is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency component $f_{1.1}$, a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency component $f_{3.1}$;

20 wherein the second metasurface pixel is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency component $f_{1.2}$, a second plasmonic resonant mode having the second frequency f_2 , and the third plasmonic resonant mode having a third frequency component $f_{3.2}$;

25 wherein the metasurface is configured to generate by a second order parametric process coherent light waves having the third frequency components $f_{3.1}$ and $f_{3.2}$ that are a sum of the first frequency components $f_{1.1}$ and $f_{1.2}$ and the second frequency f_2 ;

30 a second light propagation path from a source of pumped monochromatic coherent light waves having the second frequency f_2 to the metasurface; and

a digital image capture device substantially transparent to light waves having the first frequency components $f_{1.1}$ and $f_{1.2}$, and including a first capture pixel configured to

capture the light having the third frequency component $f_{3,1}$ generated by the first metasurface pixel and a second capture pixel configured to capture the light having the third frequency component $f_{3,2}$ generated by the second metasurface pixel.

101. The apparatus of clause 100, wherein the digital image capture device includes a
5 first capture pixel configured and aligned to directly capture the generated light having the third frequency component $f_{3,1}$ and a second capture pixel configured and aligned to capture light having the third frequency component $f_{3,2}$.

102. The apparatus of clause 100, wherein the digital image capture device is further
10 configured to output an image responsive to the light waves emanating from the object at the first frequency components $f_{1,1}$ and $f_{1,2}$.

103. The apparatus of clause 100, wherein the first metasurface pixel includes at least two first plasmonic nanoparticles, each first plasmonic nanoparticle having a respective base with a negative-permittivity layer comprising a portion the first pixel plasmonic surface.

15 104. The apparatus of clause 100, wherein the second metasurface pixel includes at least two second plasmonic nanoparticles, each having a respective base with a negative-permittivity layer comprising a portion the second pixel plasmonic surface.

105. The apparatus of clause 100, further comprising:
a first light propagation path transmitting the light waves emanating from
20 the object having the first frequency components $f_{1,1}$ and $f_{1,2}$ to the metasurface.

106. The apparatus of clause 100, further comprising:
a third light propagation path transmitting the generated light waves having
the third frequency components $f_{3,1}$ and $f_{3,2}$ from the metasurface to the digital
image capture device.

25 107. The apparatus of clause 106, further comprising:
a band block filter configured to block light at the second frequency f_2 and
interposed in the third light propagation path between the metasurface and the
digital image capture device.

108. A method comprising:
30 simultaneously receiving (i) light waves emanating from an object and having first
frequency components $f_{1,1}$ and $f_{1,2}$, and (ii) pumped monochromatic coherent light waves
having a second frequency f_2 ;

non-linearly combining the light waves having the first frequency component $f_{1.1}$ and the pumped monochromatic coherent light waves having the second frequency f_2 ;

generating by a second order parametric process coherent light waves having a third frequency component $f_{3.1}$ that is a sum of the first frequency component $f_{1.1}$ and the
 5 frequency of the second frequency f_2 ;

non-linearly combining the light waves having the first frequency component $f_{1.2}$ and the pumped monochromatic coherent light waves having the second frequency f_2 ;

generating by a second order parametric process coherent light waves having a third frequency component $f_{3.2}$ that is a sum of the first frequency $f_{1.2}$ and the second
 10 frequency f_2 ;

capturing the generated light waves having the third frequency component $f_{3.1}$;

capturing the generated light waves having the third frequency component $f_{3.2}$;

digitizing the captured light waves having the third frequency component $f_{3.1}$ and the captured light waves having the third frequency $f_{3.2}$; and

15 outputting in response to the digitized captured light waves an image responsive to the light waves frequency components $f_{1.1}$ and $f_{1.2}$ emanating from the object.

[0061] With respect to the appended claims the recited operations therein may generally be performed in any order. Also, although various operational flows are
 20 presented in a sequence(s), it should be understood that the various operations may be performed in other orders than those which are illustrated, or may be performed concurrently. Examples of such alternate orderings may include overlapping, interleaved, interrupted, reordered, incremental, preparatory, supplemental, simultaneous, reverse, or other variant orderings, unless context dictates otherwise.

25 Use of “Start,” “End,” “Stop,” or the like blocks in the block diagrams is not intended to indicate a limitation on the beginning or end of any operations or functions in the diagram. Such flowcharts or diagrams may be incorporated into other flowcharts or diagrams where additional functions are performed before or after the functions shown in the diagrams of this application. Furthermore, terms like “responsive to,” “related
 30 to,” or other past-tense adjectives are generally not intended to exclude such variants, unless context dictates otherwise.

[0062] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following

5 claims.

CLAIMS

1. An apparatus comprising:

a metasurface configured to coherently upconvert incident light waves emanating from an object and having a first frequency f_1 , the metasurface comprising:

a substrate having a first negative-permittivity layer comprising a first plasmonic surface;

a plasmonic nanoparticle having a base with a second negative-permittivity layer comprising a second plasmonic surface;

a dielectric layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface;

wherein the metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 ; and

wherein the metasurface is further configured to generate by a second order parametric process coherent light having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 ; and a second light propagation path from a source of pumped monochromatic coherent light waves having the second frequency f_2 to the metasurface; and

a digital image capture device substantially transparent to light waves having the first frequency f_1 and configured to capture the generated light waves having the frequency f_3 .

2. The apparatus of claim 1, further comprising:

a first light propagation path transmitting the light waves emanating from the object and having the first frequency f_1 to the metasurface.

3. The apparatus of claim 1, further comprising:

a third light propagation path transmitting the generated light waves having the third frequency f_3 from the metasurface to the digital image capture device.

4. The apparatus of claim 3, further comprising:

5 a band block filter configured to block light at the second frequency f_2 and interposed in the third light propagation path between the metasurface and the digital image capture device.

5. The apparatus of claim 3, wherein the third light propagation path includes at least a portion of a first light propagation path transmitting the light waves emanating from the object toward the metasurface.

10 6. The apparatus of claim 1, further comprising:

a source of pumped monochromatic coherent light waves having the second frequency f_2 and optically coupled with the second light propagation path.

7. The apparatus of claim 1, further comprising:

15 a lens configured to focus the light waves emanating from the object onto the metasurface.

8. The apparatus of claim 1, wherein the first plasmonic resonant mode frequency f_1 is spectrally separated from the second plasmonic resonant mode frequency f_2 .

9. The apparatus of claim 1, wherein the first plasmonic resonant mode frequency f_1 is a function of a first characteristic of the plasmonic nanoparticle, the second plasmonic resonant mode frequency f_2 is a function of a second characteristic of the plasmonic nanoparticle, and the third plasmonic resonant mode frequency f_3 is a function of both the first characteristic of the plasmonic nanoparticle and the second characteristic of the plasmonic nanoparticle.

10. The apparatus of claim 1, wherein the first plasmonic resonant mode frequency f_1 is a function of a first side dimension of a non-square rectangular base of the plasmonic nanoparticle, the second plasmonic resonant mode frequency f_2 is a function of a second side dimension of the non-square rectangular base of the plasmonic nanoparticle, and the third plasmonic resonant mode frequency f_3 is a function of both the first side dimension

of the non-square rectangular base of the plasmonic nanoparticle and the second side dimension of the non-square rectangular base of the plasmonic nanoparticle.

11. The apparatus of claim 1, wherein the plasmonic nanoparticle includes a base having (i) a first characteristic that establishes a first spatial mode at the first plasmonic resonant mode frequency f_1 and (ii) a second characteristic that establishes a second spatial mode at the second plasmonic resonant mode frequency f_2 , the first spatial mode and the second spatial mode overlapping each other in the dielectric layer and creating the third plasmonic resonant mode having the third frequency f_3 .
12. The apparatus of claim 1, wherein the first plasmonic resonant mode frequency f_1 and the second plasmonic resonant mode frequency f_2 are a function of the second-order nonlinear dielectric material disposed between the first plasmonic surface of the substrate and the second plasmonic surface of the plasmonic nanoparticle.
13. The apparatus of claim 1, wherein the digital image capture device is further configured to output an image responsive to the light waves emanating from the object.
14. The apparatus of claim 1, wherein the metasurface includes:
 - a substrate having a first negative-permittivity layer comprising a first plasmonic surface;
 - at least two plasmonic nanoparticles, each plasmonic nanoparticle of the at least two plasmonic nanoparticles having a respective base with a second negative-permittivity layer comprising a second plasmonic surface;
 - the dielectric layer including a second-order nonlinear material disposed between the first plasmonic surface and the respective second plasmonic surface of each of the at least two plasmonic nanoparticles; and
 - wherein the metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 ; and

wherein the metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 .

15. The apparatus of claim 1, wherein both the substrate and the base of the plasmonic
5 nanoparticle have a parallel planar geometry.
16. The apparatus of claim 1, wherein the metasurface includes a planar metasurface.
17. The apparatus of claim 1, wherein the metasurface includes a metasurface formed on a silicon chip.
18. The apparatus of claim 1, wherein the metasurface includes a metasurface on a
10 chip integrated platform.
19. The apparatus of claim 1, wherein the apparatus includes a planar apparatus.
20. The apparatus of claim 1, wherein the apparatus is formed on a silicon chip.
21. The apparatus of claim 1, wherein the apparatus is formed on a CMOS chip.
22. The apparatus of claim 1, wherein the apparatus includes on a chip integrated
15 platform.
23. The apparatus of claim 1, wherein the metasurface includes an optically thin metasurface.
24. The apparatus of claim 1, wherein the base of the plasmonic nanoparticle has a major side and a minor side shorter than the major side.
- 20 25. The apparatus of claim 24, wherein the major side corresponds to a base dimension in a first direction and the minor side corresponds to a shorter base dimension in a non-aligned direction.
26. The apparatus of claim 1, wherein the plasmonic nanoparticle includes at least two joined or proximate plasmonic nanoparticles forming the base with a second negative-
25 permittivity layer comprising the second plasmonic surface.

27. The apparatus of claim 26, wherein the at least two joined or proximate plasmonic nanoparticles form a non-square rectangular base with a second negative-permittivity layer comprising a second plasmonic surface.
28. The apparatus of claim 1, wherein the plasmonic nanoparticle includes a nanorod
5 having a non-square rectangular base with the second negative-permittivity layer.
29. The apparatus of claim 1, wherein the base of the plasmonic nanoparticle has a major side length between about 1000 and about 5000 nm.
30. The apparatus of claim 1, wherein the dielectric layer includes a dielectric layer region.
- 10 31. The apparatus of claim 1, wherein the dielectric layer includes a dielectric filled gap.
32. The apparatus of claim 1, wherein the second-order nonlinear dielectric material of the dielectric layer includes a potassium titanyl phosphate (KTP).
33. The apparatus of claim 1, wherein the second-order nonlinear dielectric material of
15 the dielectric layer includes a lithium niobate (LiNbO_3).
34. The apparatus of claim 1, wherein the second-order nonlinear dielectric material of the dielectric layer includes a second order organic dielectric material.
35. The apparatus of claim 1, wherein the dielectric layer includes a non-linear optical material having a non-linear response configured to enhance emissions at the third
20 frequency f_3 .
36. The apparatus of claim 1, wherein the plasmonic nanoparticle includes a doubly-resonant plasmonic nanoparticle.
37. The apparatus of claim 1, wherein the first negative-permittivity layer includes a metallic layer.
- 25 38. The apparatus of claim 1, wherein the first negative-permittivity layer includes a semiconductor layer or a polaritonic dielectric layer.

39. The apparatus of claim 1, wherein the second negative-permittivity layer includes a metallic layer.
40. The apparatus of claim 1, wherein the second negative-permittivity layer includes a semiconductor layer or a polaritonic dielectric layer.
- 5 41. The apparatus of claim 1, wherein the dielectric layer is less than 100 nm thick.
42. The apparatus of claim 1, wherein the dielectric layer is less than 25 nm thick.
43. The apparatus of claim 1, wherein the dielectric layer is less than 5 nm thick.
44. An apparatus comprising:
 a metasurface configured to coherently upconvert light waves emanating from
 10 an object and having a first frequency f_1 , the metasurface comprising:
 a substrate having a first negative-permittivity layer comprising a first plasmonic surface;
 a plasmonic nanoparticle having a base with a second negative-permittivity layer comprising a second plasmonic surface;
 15 a dielectric layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface;
 wherein the metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant
 20 modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 ; and
 wherein the metasurface is further configured to generate by a second order parametric process coherent light waves having the third frequency f_3
 25 that is a sum of first frequency f_1 and the second frequency f_2 ;
 a first light propagation path transmitting the light waves emanating from the object and having the first frequency f_1 to the metasurface;
 a pumped laser outputting a monochromatic coherent light having the second frequency f_2 ;

a second light propagation path transmitting monochromatic coherent light having the second frequency f_2 from the pumped laser to the metasurface;

a digital image capture device substantially transparent to the light waves having the first frequency f_1 , and configured to (i) capture the generated light waves having the third frequency f_3 and (ii) output an image responsive to the light waves emanating from the object; and

a third light propagation path transmitting the generated light waves having the third frequency f_3 from the metasurface to the digital image capture device.

45. A method comprising:

simultaneously receiving in a thin planar metasurface (i) light waves emanating from an object and having a first frequency f_1 and (ii) pumped monochromatic coherent light waves having a second frequency f_2 ;

non-linearly combining in the thin planar metasurface the light waves having the first frequency f_1 and the pumped monochromatic coherent light waves having the second frequency f_2 ;

generating in the thin planar metasurface by a second order parametric process coherent light waves having a third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 ;

digitizing the generated light waves having the frequency f_3 ; and

outputting in response to the digitized generated light waves a digital image responsive to the light waves emanating from the object.

46. The method of claim 45, wherein the thin planar metasurface includes a thin planar metasurface having a subwavelength thickness relative to f_1 or f_2 .

47. The method of claim 45, further comprising:

blocking light waves at the second frequency f_2 from reaching the digital image capture device.

48. A metasurface configured to coherently upconvert incident light waves having a first frequency f_1 , the metasurface comprising:

a substrate having a first negative-permittivity layer comprising a first plasmonic surface;

a plasmonic nanoparticle having a base with a second negative-permittivity layer comprising a second plasmonic surface;

a dielectric layer comprising a second-order nonlinear dielectric material disposed between the first plasmonic surface and the second plasmonic surface;

5 wherein the metasurface is configured to form at least three plasmonic resonant modes in the dielectric layer, the at least three plasmonic resonant modes including a first plasmonic resonant mode having the first frequency f_1 , a second plasmonic resonant mode having a second frequency f_2 , and a third plasmonic resonant mode having a third frequency f_3 ; and

10 wherein the metasurface is further configured to generate by a second order parametric process coherent light having the third frequency f_3 that is a sum of the first frequency f_1 and the second frequency f_2 .

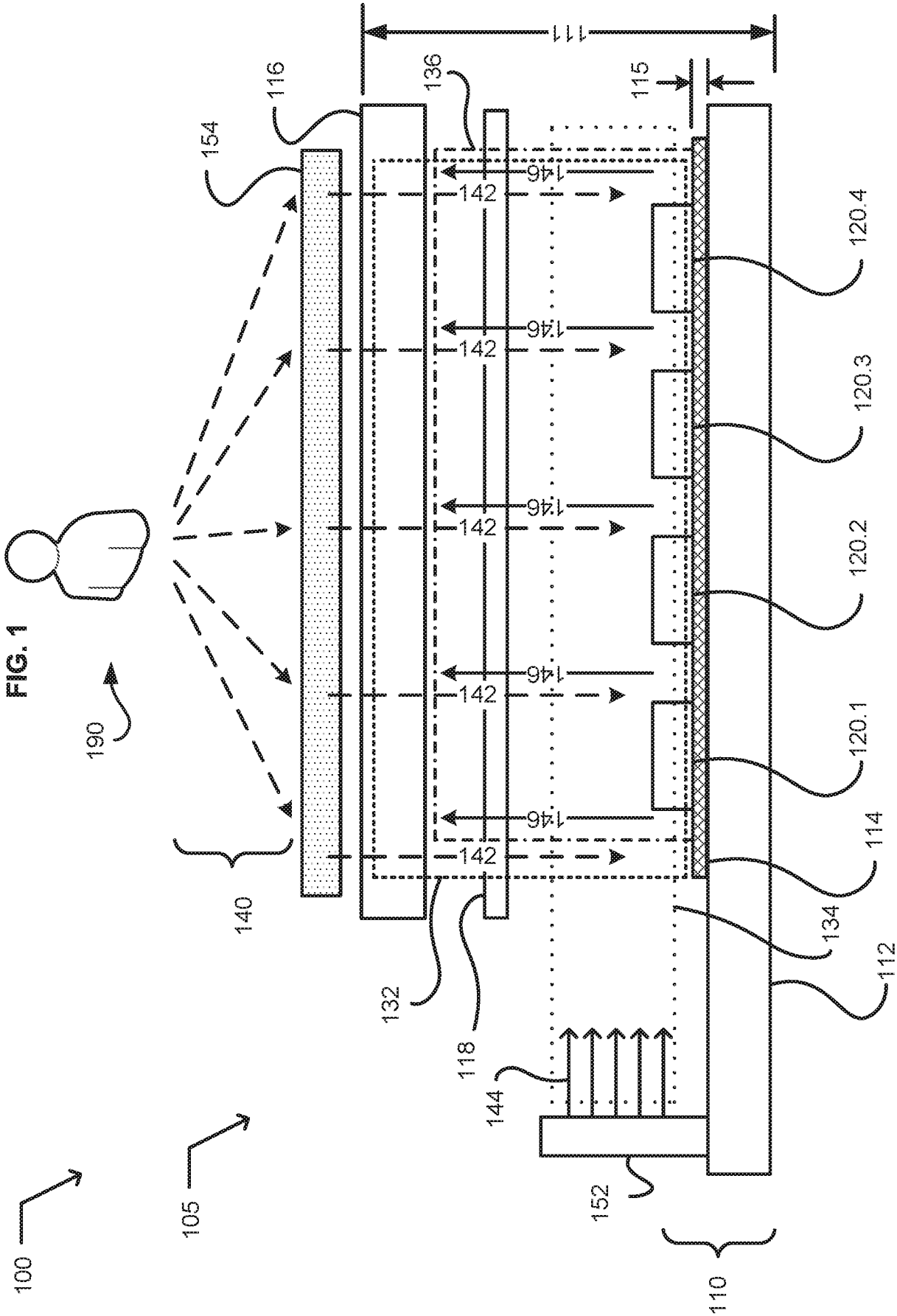
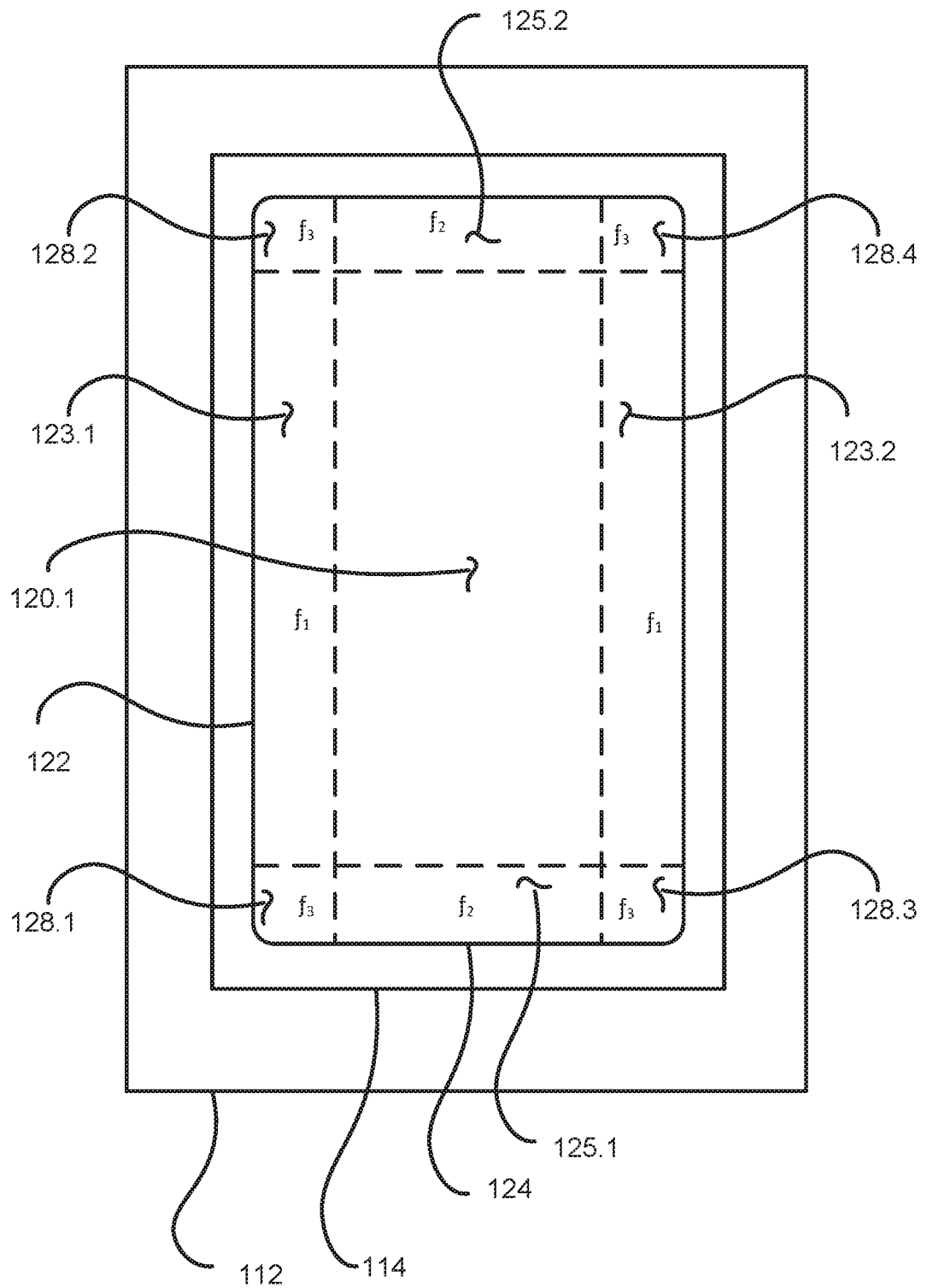


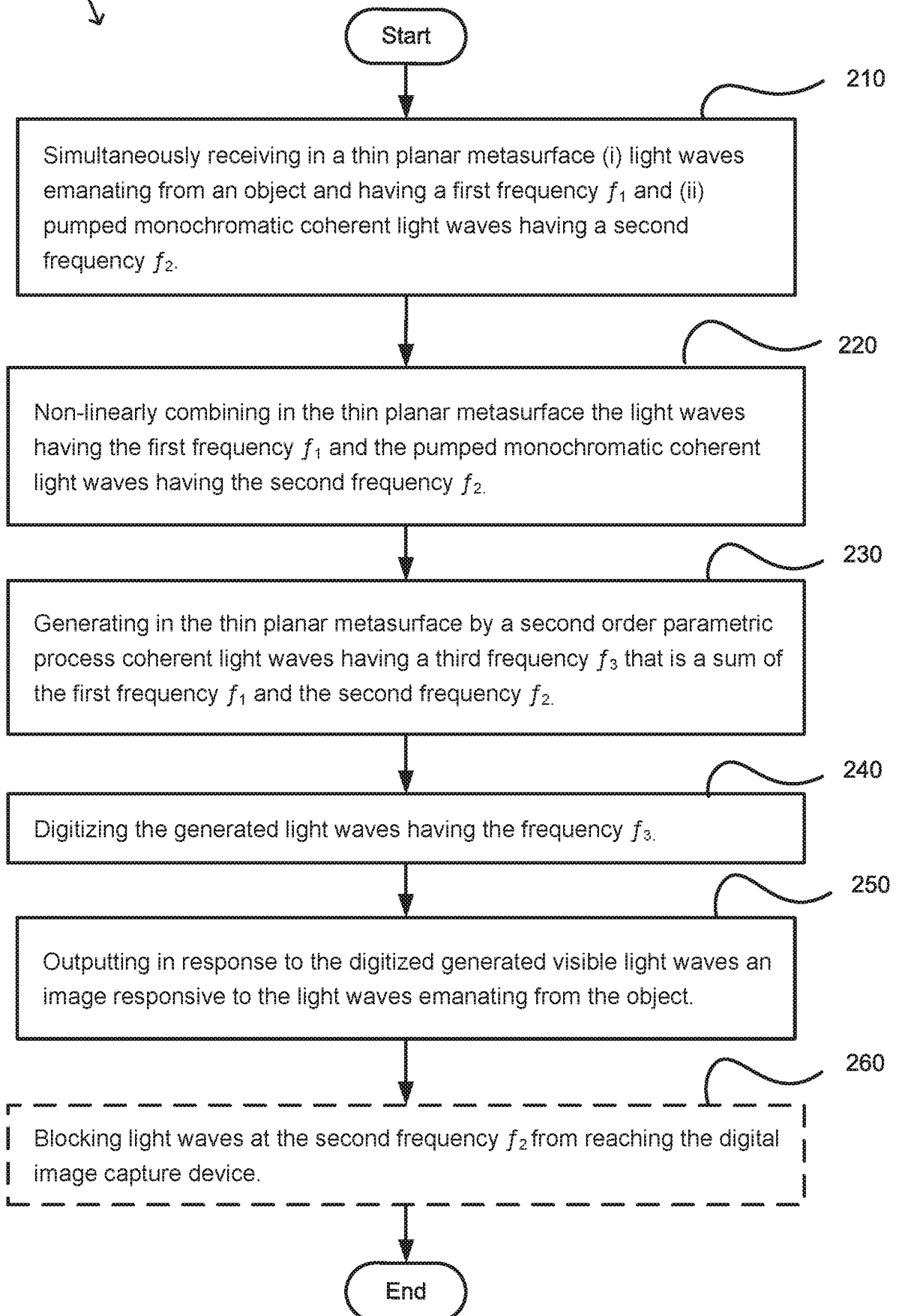
FIG. 2



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FIG. 3

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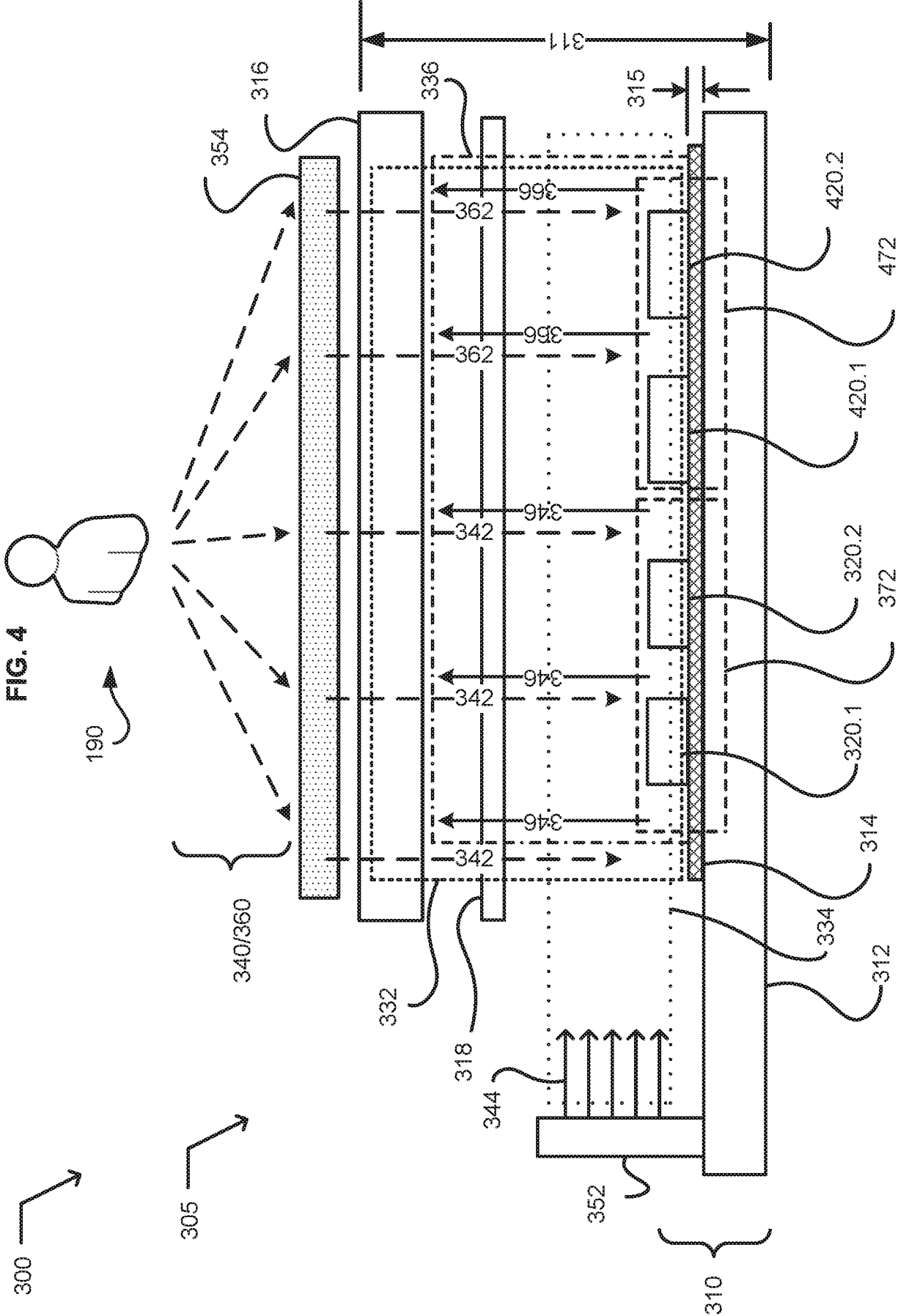
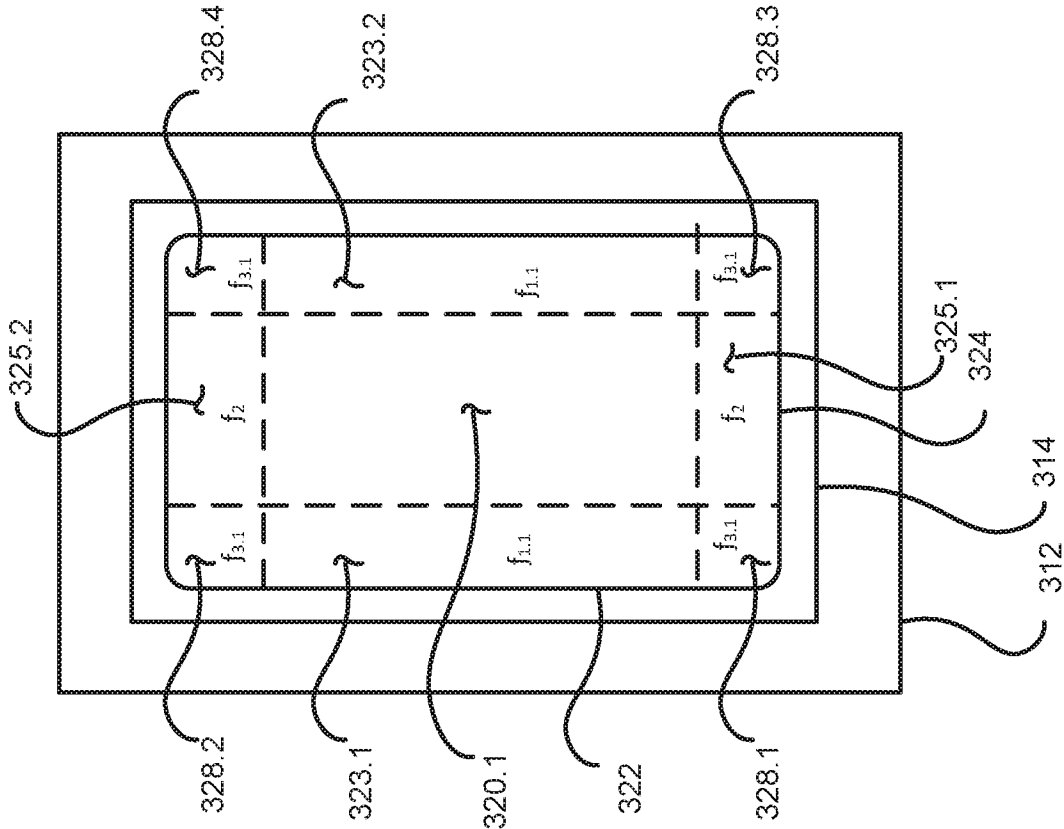
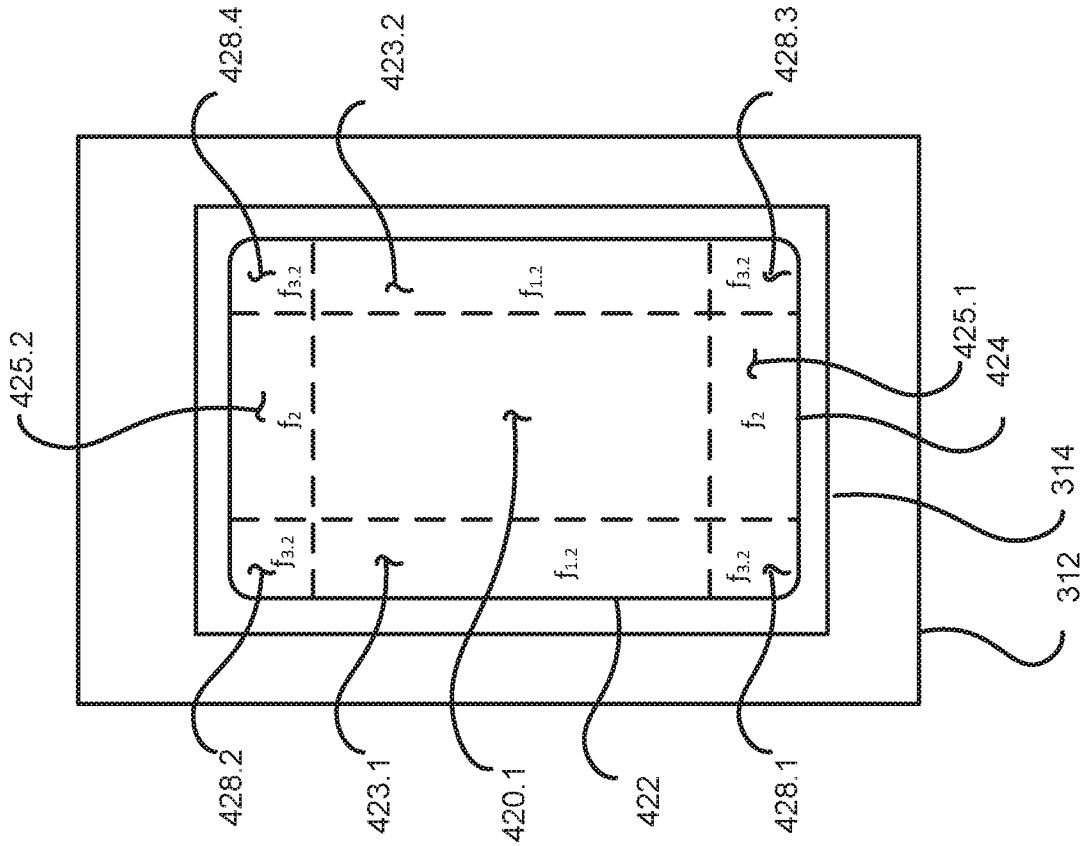
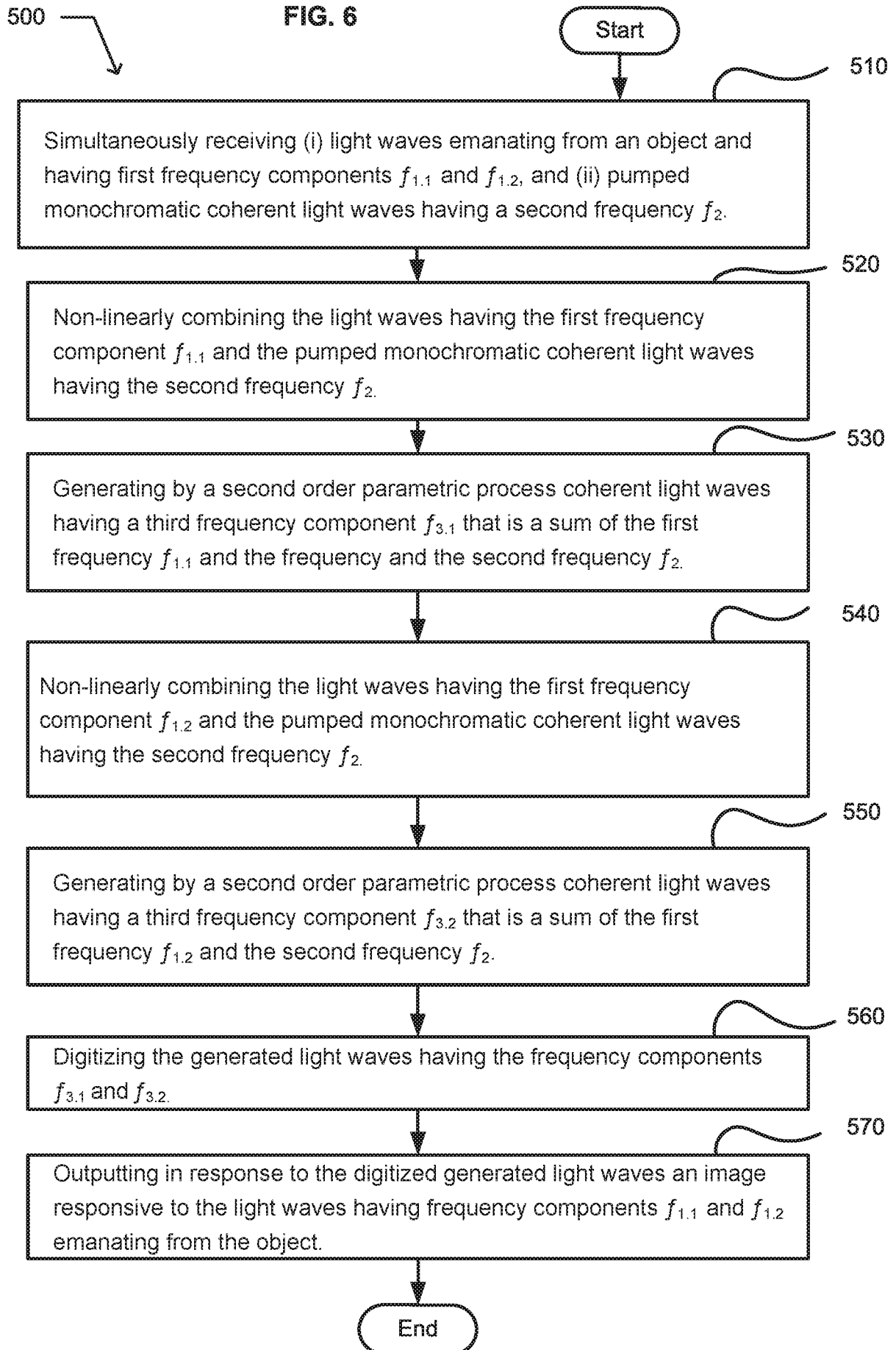


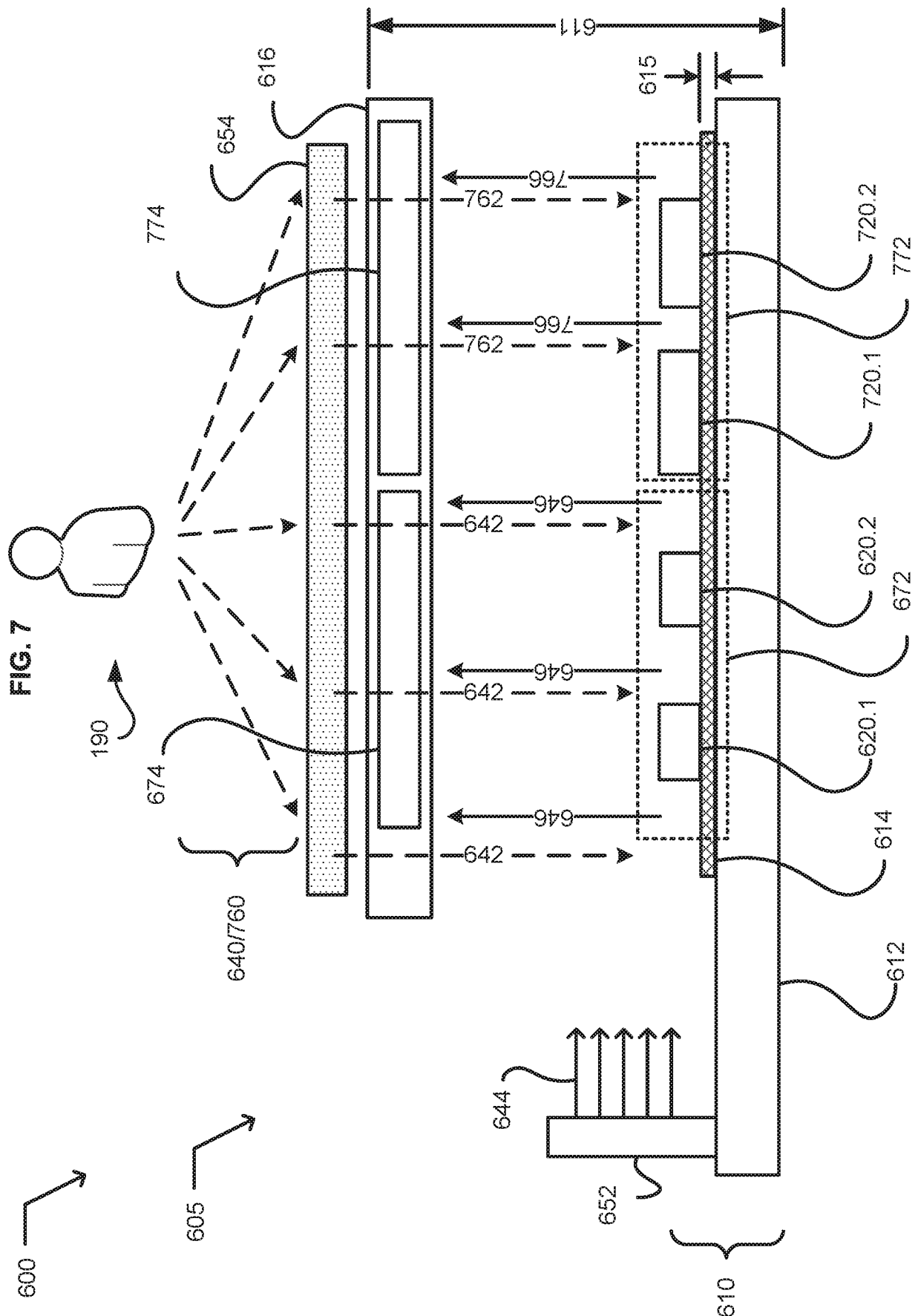
FIG. 5



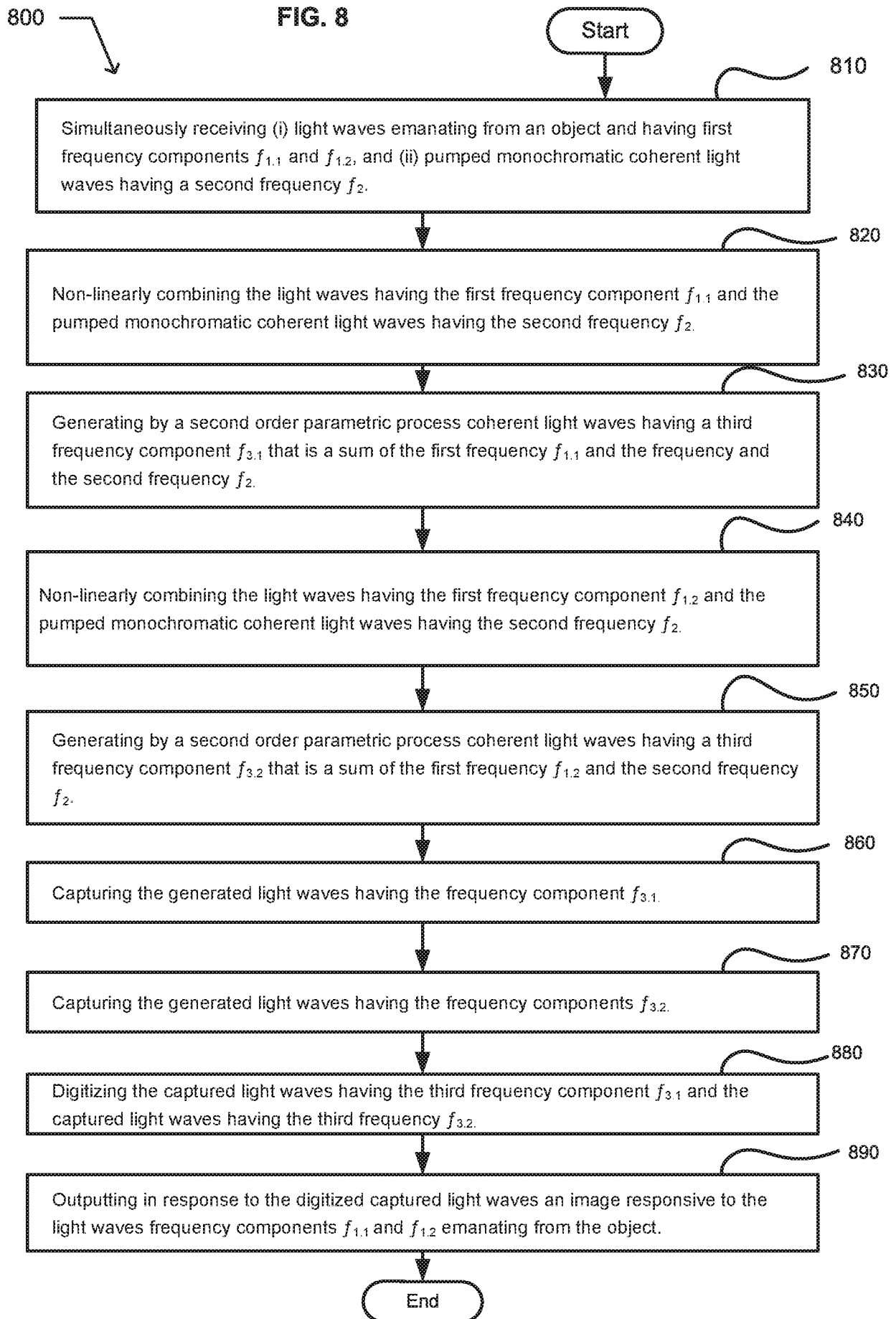
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/060638**A. CLASSIFICATION OF SUBJECT MATTER****G02F 1/35(2006.01)i, G02F 1/01(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02F 1/35; A61N 5/06; H01L 27/146; A61N 5/00; G01T 1/24; H01S 3/108; F21K 2/00; G21G 4/00; H01L 31/0232; H01S 3/091; G02F 1/01

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: coherently upconvert, second order parametric process, pumped laser, capture

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2016-0301181 A1 (ELWHA LLC) 13 October 2016 See paragraphs [0017]-[0025]; and figures 1-5.	1-48
A	US 2013-0171060 A1 (IMMUNOLIGHT, LLC) 04 July 2013 See claims 1-57.	1-48
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Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

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Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea

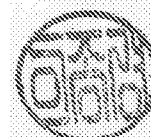


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