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(54) **SUBWAVELENGTH GRATING COUPLER**

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(51) **Int. Cl.**

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G06F 17/50	(2006.01)
G02B 6/124	(2006.01)
G02B 6/126	(2006.01)
G02B 6/13	(2006.01)
G02B 6/136	(2006.01)

(52) **U.S. Cl.**
CPC ***G06F 17/50*** (2013.01); ***G02B 6/124*** (2013.01); *G02B 6/126* (2013.01); *G02B 6/13* (2013.01); *G02B 6/136* (2013.01)

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CPC G02B 6/126; G02B 6/2746; G02B 6/105; G02B 6/124; G02B 6/02085; G02B 6/12007; G06F 17/5018; G06F 17/5036; G06F 17/5009
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See application file for complete search history.

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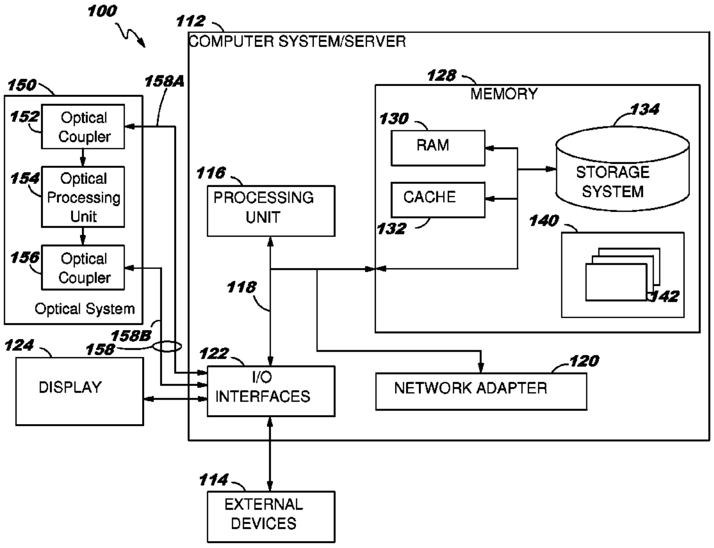
(74) *Attorney, Agent, or Firm* — Paul S. Drake

(57) **ABSTRACT**

A method, system or device for configuring an optical coupling device including obtaining characteristics of an optical signal and ambient conditions for storage in memory, utilizing a processor for identifying an optimum effective subwavelength area refractive index and a grating period for the input signal and ambient characteristics stored in memory, and utilizing the processor for identifying a preferred filling factor for a transverse polarization.

20 Claims, 8 Drawing Sheets



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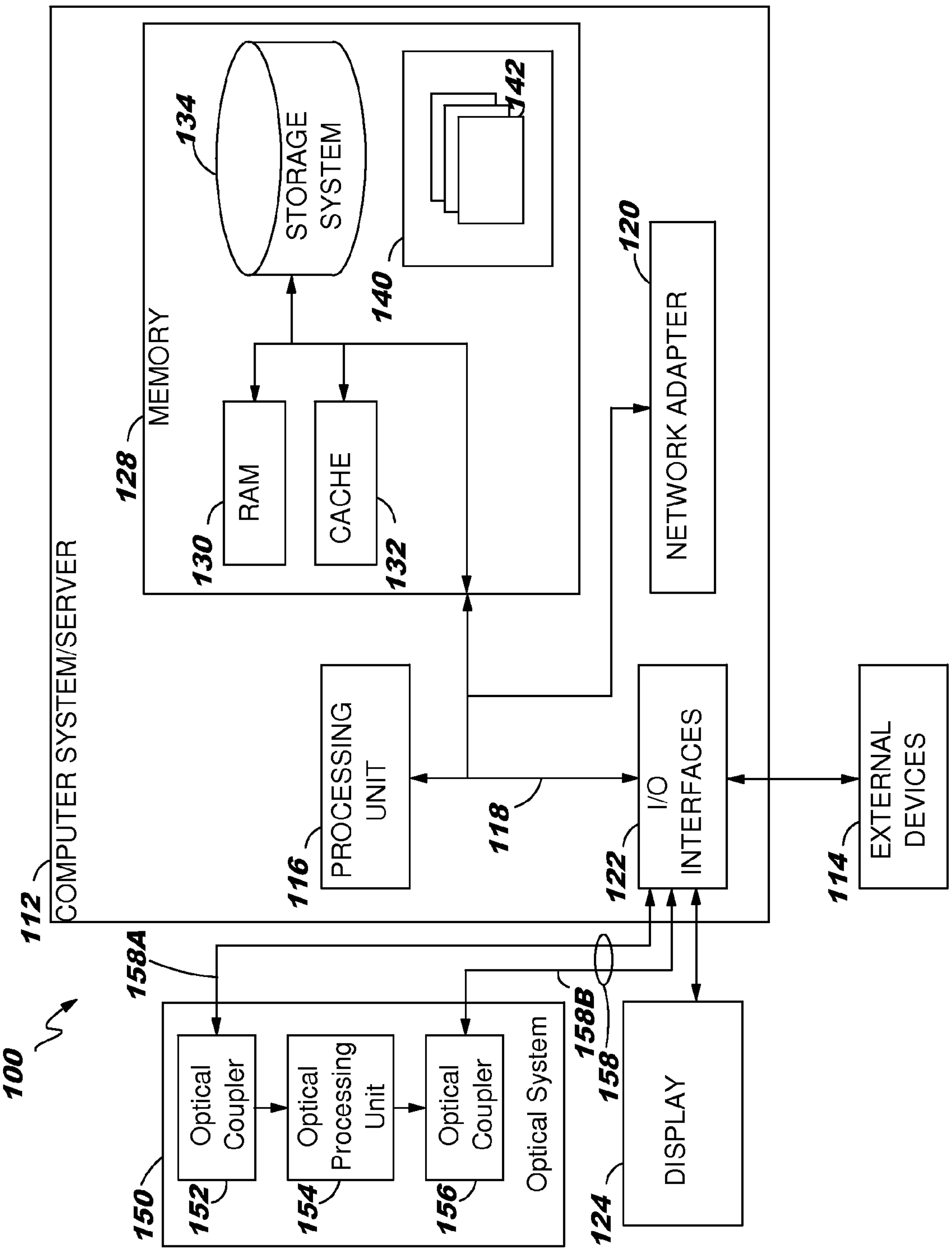
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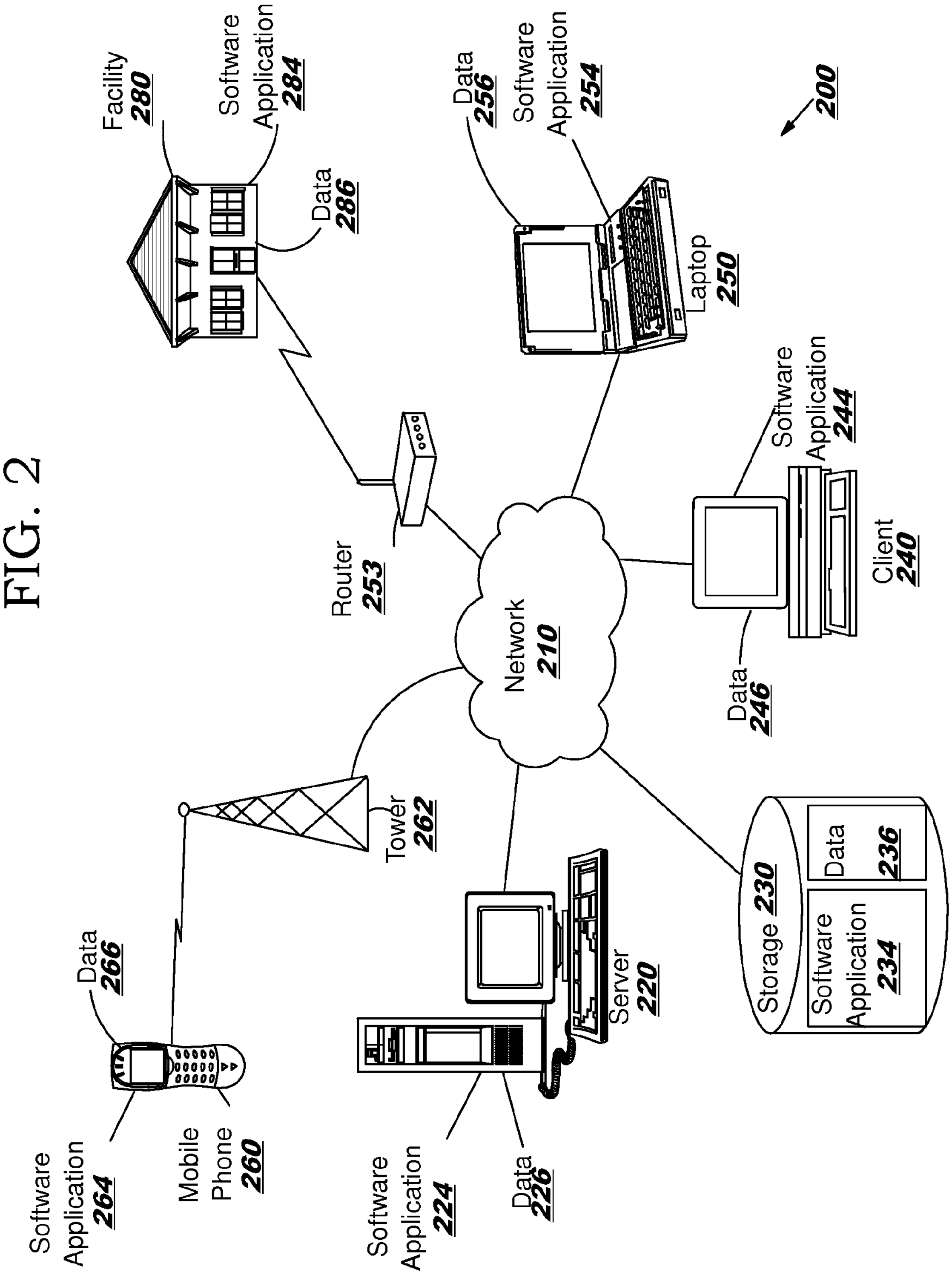
112
COMPUTER SYSTEM/SERVER
128
MEMORY
130
RAM
132
CACHE
134
STORAGE SYSTEM
140
142
120
NETWORK ADAPTER
116
PROCESSING UNIT
118
122
I/O INTERFACES
114
EXTERNAL DEVICES
158A
158B
158
124
DISPLAY
150
Optical System
152
Optical Coupler
154
Optical Processing Unit
156
Optical Coupler

FIG. 1

FIG. 2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Software Application 284
Data 286
Data 256
Software Application 254
Laptop 250
200
Router 253
Network 210
Software Application 244
Client 240
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Data 266
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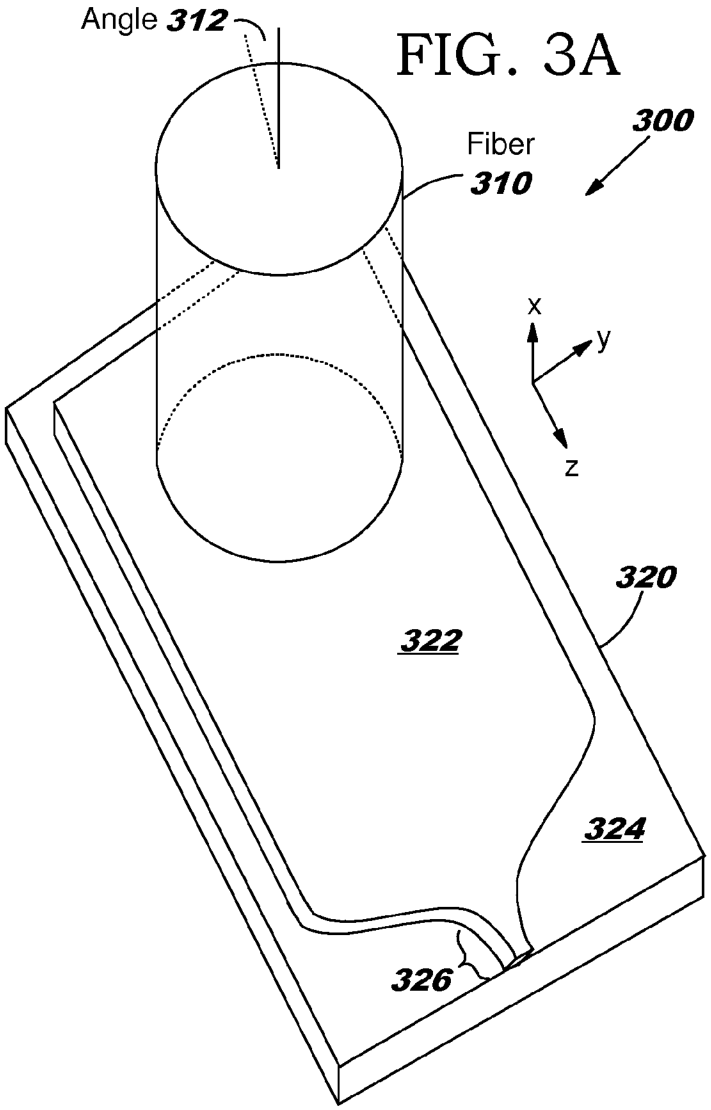
Mobile Phone 260
Server 220
Software Application 224
Data 226
Storage 230
Data 236
Software Application 234

FIG. 3A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Fiber
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x
y
z
320
322
324
326

FIG. 3B

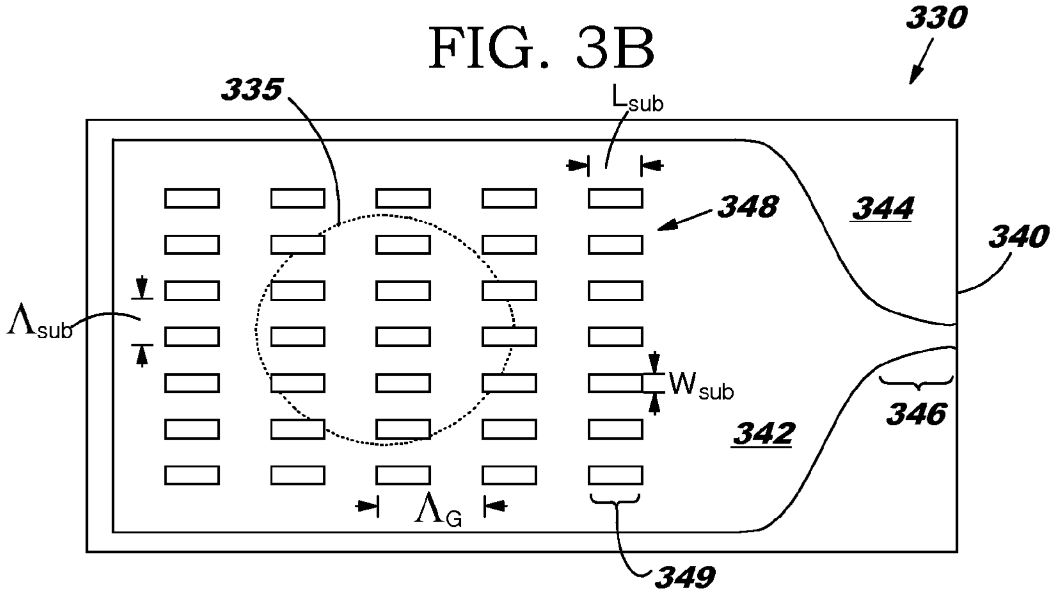
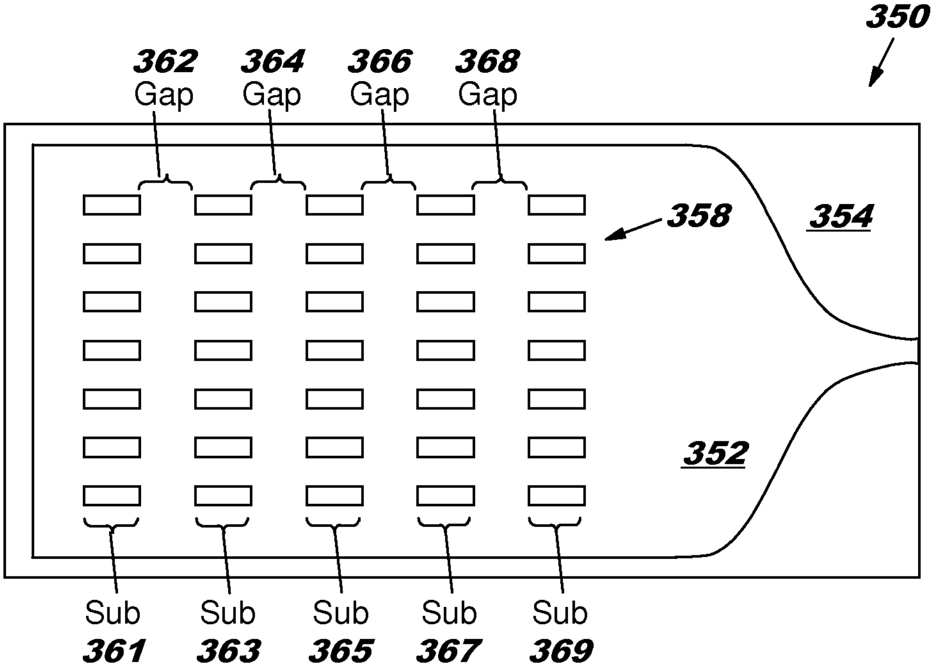

330
335
L_{sub}
348
344
340
Λ_{sub}
W_{sub}
342
346
Λ_G
349

FIG. 3C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Gap
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Gap
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Gap
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Gap
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Sub
369

FIG. 3D

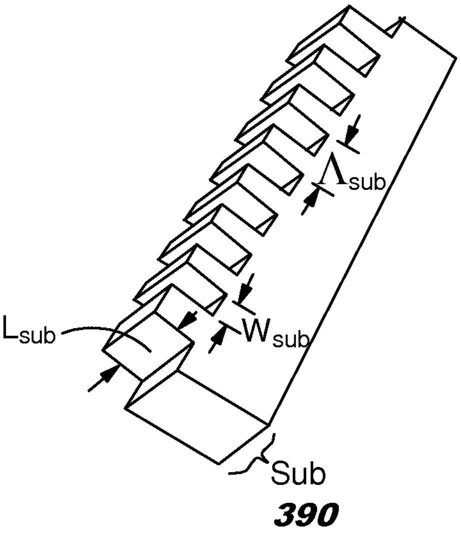
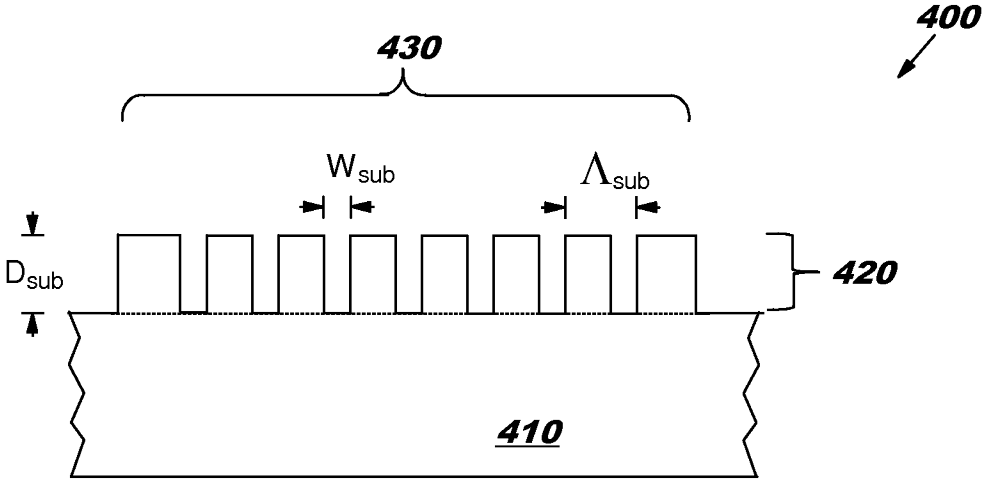
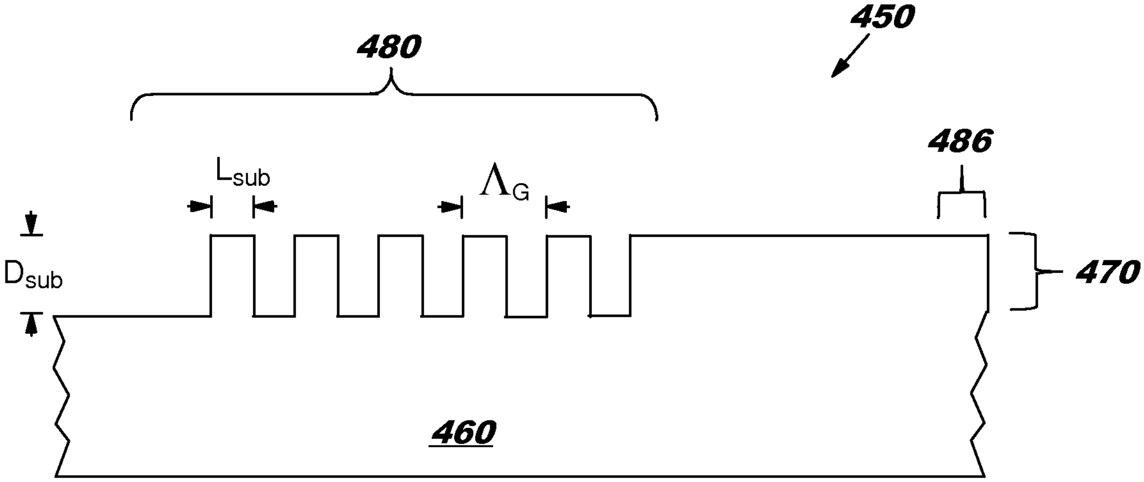

Λ_{sub}
W_{sub}
L_{sub}
Sub
390

FIG. 4A



400
430
W_{sub}
Λ_{sub}
D_{sub}
420
410

FIG. 4B



450
480
L_{sub}
Λ_G
486
D_{sub}
470
460

FIG. 5A

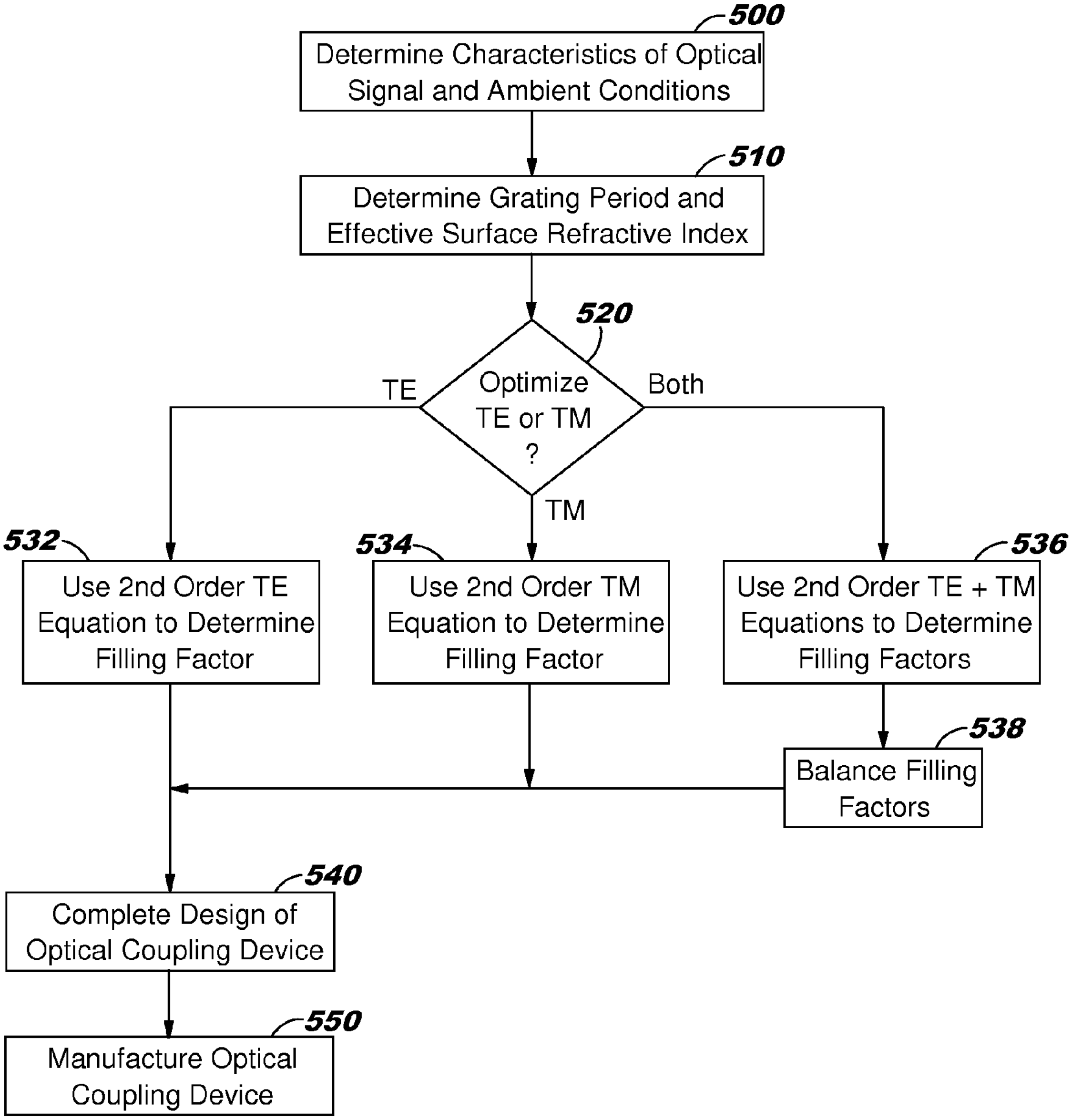
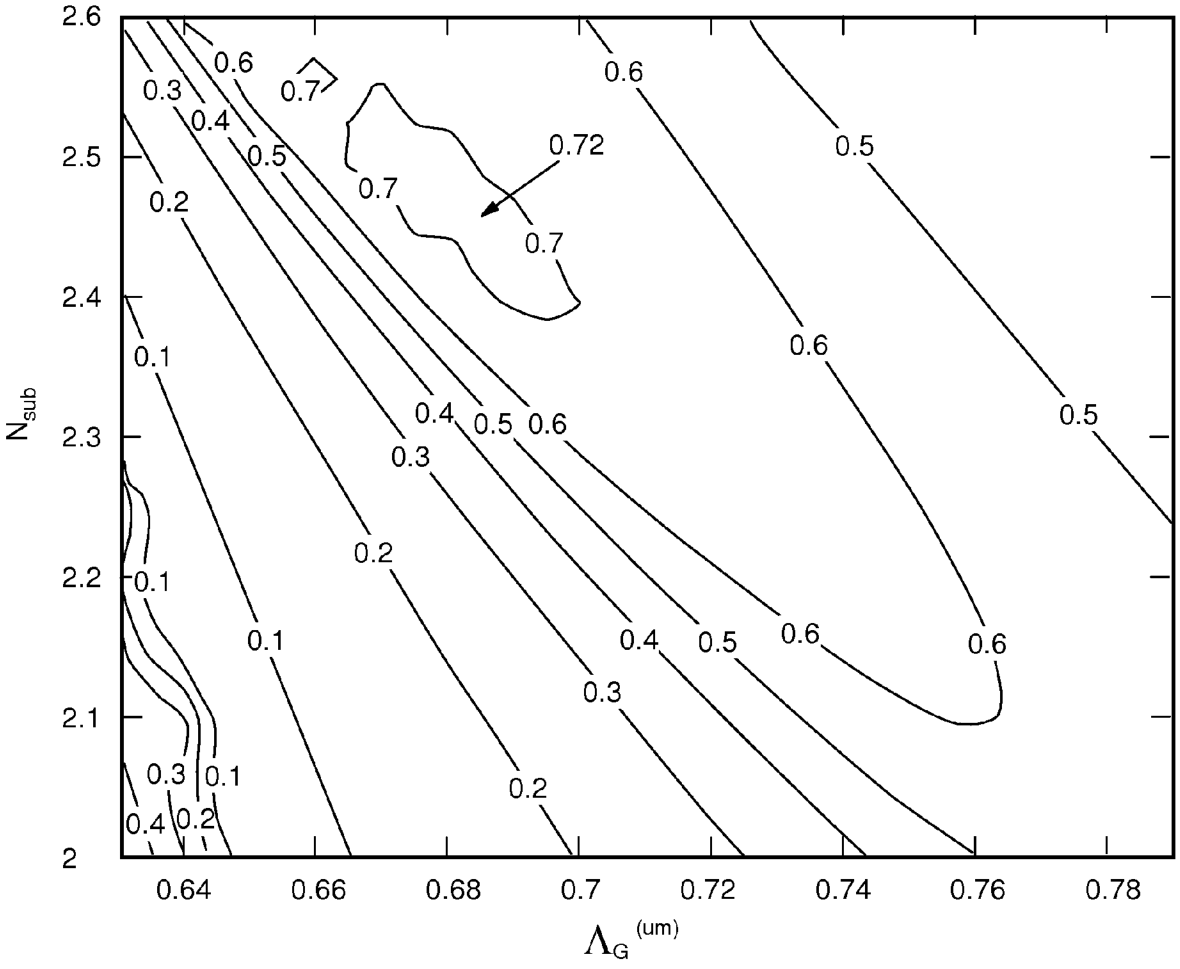

500
Determine Characteristics of Optical Signal and Ambient Conditions
510
Determine Grating Period and Effective Surface Refractive Index
520
Optimize TE or TM ?
TE
Both
TM
532
Use 2nd Order TE Equation to Determine Filling Factor
534
Use 2nd Order TM Equation to Determine Filling Factor
536
Use 2nd Order TE + TM Equations to Determine Filling Factors
538
Balance Filling Factors
540
Complete Design of Optical Coupling Device
550
Manufacture Optical Coupling Device

FIG. 5B



2.6
2.5
2.4
2.3
2.2
2.1
2
N_{sub}
0.64
0.66
0.68
0.7
0.72
0.74
0.76
0.78
Λ_G (um)
0.72
0.7
0.6
0.5
0.4
0.3
0.2
0.1

FIG. 6A

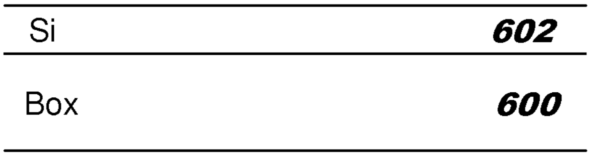


FIG. 6B

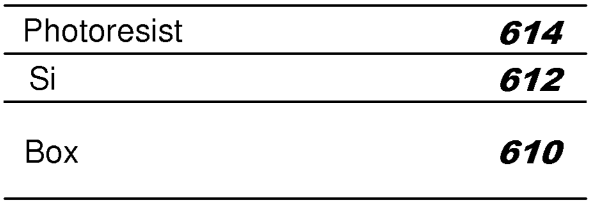


FIG. 6C

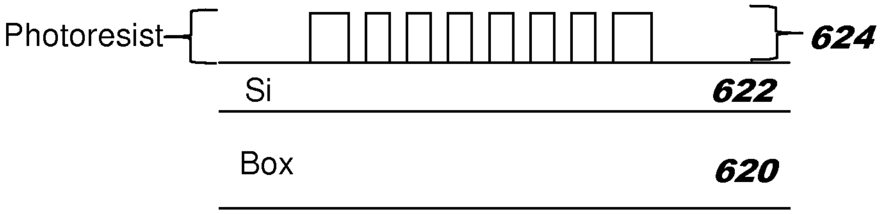


FIG. 6D

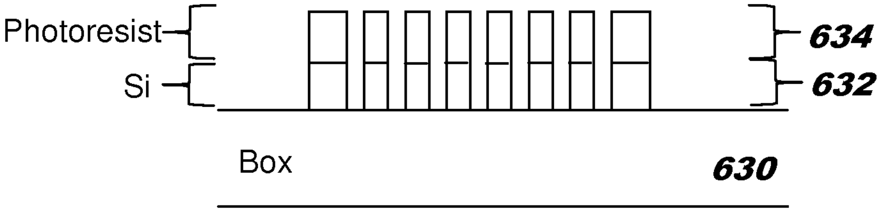
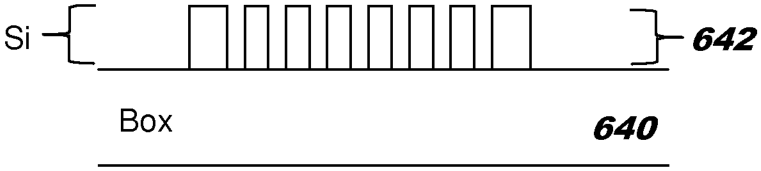


FIG. 6E



SUBWAVELENGTH GRATING COUPLER

This application claims priority to U.S. Provisional Application No. 61/770,694 entitled "Subwavelength Grating Coupler" filed Feb. 28, 2013.

This invention was made with government support under FA9550-08-1-0394 and FA9550-11-C-0014 awarded by the Air Force Office of Scientific Research. The government has certain rights in the invention.

BACKGROUND

1. Technical Field

The present invention relates generally to an optical grating coupler, and in particular, to a subwavelength grating coupler for silicon integrated photonics.

2. Description of Related Art

Guided wave optical devices and systems are being utilized in many applications in the telecommunications, cable television, instrumentation and computation industries. A variety of devices have been developed and utilized in implementing the use of guided waves for communicating information. These devices include the use of fiber optic cables for transmitting optical signals over longer distances and higher bandwidths than many other forms of communication. These devices also include planar optical waveguides in which optical signals are confined to narrow channels on a roughly two dimensional surface such as a silicon chip where the optical signals are routed, split, filtered, multiplexed and demultiplexed, switched, sensed, etc. as guided waves. By utilizing planar optical waveguides on silicon chips or other similar materials, a tremendous amount of existing technology is available for the manufacturing of these devices.

Various types of couplers are utilized for transitioning optical signals from a fiber optic cable to a silicon chip surface waveguide including prism couplers and grating couplers. There are many varieties of these couplers with varying characteristics such as efficiency, bandwidth, and manufacturability.

SUMMARY

The illustrative embodiments provide a method, system or device for configuring an optical coupling device including obtaining characteristics of an optical signal and ambient conditions for storage in memory, utilizing a processor for identifying an optimum effective subwavelength area refractive index and a grating period for the input signal and ambient characteristics stored in memory, and utilizing the processor for identifying a preferred filling factor for a transverse polarization.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, further objectives and advantages thereof, as well as a preferred mode of use, will best be understood by reference to the following detailed description of illustrative embodiments when read in conjunction with the accompanying drawings, wherein:

FIG. **1** is a block diagram of a data processing system in which various embodiments may be implemented;

FIG. **2** is a block diagram of a network of data processing systems in which various embodiments may be implemented;

FIG. **3**A is a perspective view of an optical coupling system in which various embodiments may be implemented;

FIGS. **3**B and **3**C is an overhead view of the optical coupling system in which various embodiments may be implemented;

FIG. **3**D is a perspective cutaway view of a subwavelength region of the grating area in which various embodiments may be implemented;

FIGS. **4**A and **4**B are widthwise and lengthwise cutaway views of the optical coupling device in which various embodiments may be implemented;

FIG. **5**A is a flow diagram of a process for configuring an optical coupling device in which various embodiments may be implemented;

FIG. **5**B is a diagram of a relationship between subwavelength structure refractive index, grating period and efficiency for a given optical signal wavelength; and

FIGS. **6**A through **6**E are widthwise cutaway views of the optical coupling device being manufactured in which various embodiments may be implemented.

DETAILED DESCRIPTION

Processes and devices may be implemented and utilized to provide a subwavelength grating coupler between a fiber optic cable and an optical waveguide. These processes and apparatuses may be implemented and utilized as will be explained with reference to the various embodiments below.

FIG. **1** is a block diagram of a data processing system in which various embodiments may be implemented. Data processing system **100** is one example of a suitable data processing system and is not intended to suggest any limitation as to the scope of use or functionality of embodiments of the invention described herein. Regardless, data processing system **100** is capable of being implemented and/or performing any of the functionality set forth herein.

In data processing system **100** there is a computer system/server **112**, which is operational with numerous other general purpose or special purpose computing system environments, peripherals, or configurations. Examples of well-known computing systems, environments, and/or configurations that may be suitable for use with computer system/server **112** include, but are not limited to, personal computer systems, server computer systems, thin clients, thick clients, hand-held or laptop devices, multiprocessor systems, microprocessor-based systems, set top boxes, programmable consumer electronics, network PCs, minicomputer systems, mainframe computer systems, and distributed cloud computing environments that include any of the above systems or devices, and the like.

Computer system/server **112** may be described in the general context of computer system-executable instructions, such as program modules, being executed by a computer system. Generally, program modules may include routines, programs, objects, components, logic, data structures, and so on that perform particular tasks or implement particular abstract data types. Computer system/server **112** may be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules may be located in both local and remote computer system storage media including memory storage devices.

As shown in FIG. **1**, computer system/server **112** in data processing system **100** is shown in the form of a general-purpose computing device. The components of computer system/server **112** may include, but are not limited to, one or more processors or processing units **116**, a system memory **128**, and a bus **118** that couples various system components including system memory **128** to processor **116**. These and other components may utilize optical communications with other components or even within a component. Such optical communications can include fiber optic cables and may utilize optical couplers between the fiber optical cables and the optical waveguides (e.g. planar or rectangular) on silicon chips or other planar substrates.

Bus **118** represents one or more of any of several types of bus structures, including a memory bus or memory controller, a peripheral bus, an accelerated graphics port, and a processor or local bus using any of a variety of bus architectures. By way of example, and not limitation, such architectures include Industry Standard Architecture (ISA) bus, Micro Channel Architecture (MCA) bus, Enhanced ISA (EISA) bus, Video Electronics Standards Association (VESA) local bus, and Peripheral Component Interconnects (PCI) bus.

Computer system/server **112** typically includes a variety of computer system readable media. Such media may be any available media that is accessible by computer system/server **112**, and it includes both volatile and non-volatile media, removable and non-removable media.

System memory **128** can include computer system readable media in the form of volatile memory, such as random access memory (RAM) **130** and/or cache memory **132**. Computer system/server **112** may further include other removable/non-removable, volatile/non-volatile computer system storage media. By way of example, storage system **134** can be provided for reading from and writing to a non-removable, non-volatile magnetic media (not shown and typically called a "hard drive"). Although not shown, a magnetic disk drive for reading from and writing to a removable, non-volatile magnetic disk (e.g., a "floppy disk"), and an optical disk drive for reading from or writing to a removable, non-volatile optical disk such as a CD-ROM, DVD-ROM or other optical media can be provided. In such instances, each can be connected to bus **118** by one or more data media interfaces. Memory **128** may include at least one program product having a set (e.g., at least one) of program modules that are configured to carry out the functions of embodiments of the invention. Memory **128** may also include data that will be processed by a program product.

Program/utility **140**, having a set (at least one) of program modules **142**, may be stored in memory **128** by way of example, and not limitation, as well as an operating system, one or more application programs, other program modules, and program data. Each of the operating system, one or more application programs, other program modules, and program data or some combination thereof, may include an implementation of a networking environment. Program modules **142** generally carry out the functions and/or methodologies of embodiments of the invention.

An optical system **150** may also communicate with a computer system or server through optical fibers **158** and I/O interface **122**. I/O interface **122** or other device in communication with system **112** may provide an optical signal or beam (such as a laser beam) through optical fiber **158**A to optical coupler **152** to optical processing unit **154**. Optical processing unit **154** may then utilize the optical signal or beam to perform certain tasks such as biosensing, signal processing, etc., before returning the optical signal through optical coupler **156** back to I/O interface **122** through optical fiber **158**B. Optical processing unit may include optical components, electronic components, chemical components, biological components etc. for processing the optical signal received through optical fiber **158**A. For example, optical system **150** may be a testing device that utilizes optical signals or an optical beam for detection purposes. Optical system **150** may also be a communications network that utilizes DWDM (dense wavelength division multiplexing) for S, C and L bands. The return signal to system **112** may also be a non-optical signal such as an electronic signal. I/O interface **122** may also utilize optical waveguides in the process of communicating with optical system **150**.

Computer system/server **112** may also communicate with one or more external devices **114** such as a keyboard, a pointing device, a display **124**, etc.; one or more devices that enable a user to interact with computer system/server **112**; and/or any devices (e.g., network card, modem, etc.) that enable computer system/server **112** to communicate with one or more other computing devices. Such communication can occur via I/O interfaces **122** through wired connections, optical connections, or wireless connections. Still yet, computer system/server **112** can communicate with one or more networks such as a local area network (LAN), a general wide area network (WAN), and/or a public network (e.g., the Internet) via network adapter **120**. As depicted, network adapter **120** communicates with the other components of computer system/server **112** via bus **118**. It should be understood that although not shown, other electrical and optical hardware and/or software components could be used in conjunction with computer system/server **112**. Examples, include, but are not limited to: microcode, device drivers, tape drives, RAID systems, redundant processing units, data archival storage systems, external disk drive arrays, etc.

FIG. **2** is a block diagram of a network of data processing systems in which various embodiments may be implemented. Data processing environment **200** is a network of data processing systems such as described above with reference to FIG. **1**. Software applications may execute on any computer or other type of data processing system in data processing environment **200**. Data processing environment **200** includes network **210**. Network **210** is the medium used to provide simplex, half duplex and/or full duplex communications links between various devices and computers connected together within data processing environment **200**. Network **210** may include connections such as wire, wireless communication links, or fiber optic cables including the use of optical couplers.

Server **220** and client **240** are coupled to network **210** along with storage unit **230**. In addition, laptop **250** and facility **280** (such as a home or business) are coupled to network **210** including wirelessly such as through a network router **253**. A mobile phone **260** may be coupled to network **210** through a mobile phone tower **262**. Data processing systems, such as server **220**, client **240**, laptop **250**, mobile phone **260** and facility **280** contain data and have software applications including software tools executing thereon. Other types of data processing systems such as personal digital assistants (PDAs), smartphones, tablets and netbooks may be coupled to network **210**.

Server **220** may include software application **224** and data **226** for software applications and data in accordance with embodiments described herein. Storage **230** may contain software application **234** and a content source such as data **236**. Other software and content may be stored on storage **230** for sharing among various computer or other data processing devices. Client **240** may include software application **244** and data **246**. Laptop **250** and mobile phone **260** may also include software applications **254** and **264** and data **256** and **266**. Facility **280** may include software applications **284** and data **286**. Other types of data processing systems coupled to network **210** may also include software applications. Software applications could include a web browser, email, or other software application.

Server **220**, storage unit **230**, client **240**, laptop **250**, mobile phone **260**, and facility **280** and other data processing devices may couple to network **210** using wired connections, wireless communication protocols, or other suitable data connectivity. Client **240** may be, for example, a personal computer or a network computer.

In the depicted example, server **220** may provide data, such as boot files, operating system images, and applications to client **240** and laptop **250**. Server **220** may be a single computer system or a set of multiple computer systems working together to provide services in a client server environment. Client **240** and laptop **250** may be clients to server **220** in this example. Client **240**, laptop **250**, mobile phone **260** and facility **280** or some combination thereof, may include their own data, boot files, operating system images, and applications. Data processing environment **200** may include additional servers, clients, and other devices that are not shown.

In the depicted example, data processing environment **200** may be the Internet. Network **210** may represent a collection of networks and gateways that use the Transmission Control Protocol/Internet Protocol (TCP/IP) and other protocols to communicate with one another. At the heart of the Internet is a backbone of data communication links between major nodes or host computers, including thousands of commercial, governmental, educational, and other computer systems that route data and messages. Of course, data processing environment **200** also may be implemented as a number of different types of networks, such as for example, an intranet, a local area network (LAN), or a wide area network (WAN). Each of these networks may utilize optical fibers for transmitting or receiving information through optical couplers to various components of the data processing systems. FIG. **2** is intended as an example, and not as an architectural limitation for the different illustrative embodiments.

Among other uses, data processing environment **200** may be used for implementing a client server environment in which the embodiments may be implemented. A client server environment enables software applications and data to be distributed across a network such that an application functions by using the interactivity between a client data processing system and a server data processing system. Data processing environment **200** may also employ a service oriented architecture where interoperable software components distributed across a network may be packaged together as coherent business applications.

FIG. **3**A is a perspective view of an optical coupling system **300** in which various embodiments may be implemented. An optical fiber **310** is shown nearly orthogonal to and adjoining an optical coupling device **320**. Optical coupling device **320** may be a discrete device or it may be planar with many other types of devices on a common substrate. Optical coupling device **320** includes an optical coupler **322** on top of substrate **324**. Optical coupler **322** may be constructed of silicon or similar material. Substrate **324** may continue in the plane of the device and may contain many such devices. Substrate **324** may be an insulator such as silicon dioxide to provide electrical isolation from other devices. Also shown is an optical waveguide **326** for transmitting optical information to or from other devices planar to optical coupler **322**. Optical coupler is bidirectional so the optical signal can travel in either direction. Not shown in this figure is a grating in optical coupler **322** and under fiber **310**.

Optical fiber **310** is at a Θ angle **312** where the foot or butt of optical fiber is open towards (leaning away from) optical waveguide **326**. Optical fiber may be help in place by a mechanical holder or other similar device. As a result, when an optical signal travels down the length of optical fiber **310**, that signal strikes optical coupler **322** at Θ angle **312**, and is then guided down waveguide **326** towards another coplanar optical device for handling. In addition, an optical signal may be guided up waveguide **326** from another coplanar optical device. That signal strikes optical coupler **322** and then travels up optical fiber **310** at Θ angle **312**.

Also shown is the x, y and z axis directions of the optical fiber and optical coupler. The x direction is roughly in the direction of the optical fiber (the optical fiber is slightly angled from being orthogonal from the optical coupler) and is roughly the direction that light travels down the optical fiber to the optical coupler. The optical coupler is planar in the y and z directions, with the waveguide being in the z direction from the optical fiber. Θ angle **312** is in the z direction.

FIG. **3**B is an overhead view of the optical coupling system **330** in which various embodiments may be implemented. An optical fiber **335** is shown in outline form nearly orthogonal to and adjoining an optical coupling device **340**. Optical coupling device **340** may be a discrete device or it may be planar with many other types of devices on a common substrate. Optical coupling device **340** includes an optical coupler **342** on top of substrate **344**. Optical coupler **342** may be constructed of silicon or similar material. Substrate **344** may continue in the plane of the device and may contain many such devices. Substrate **344** may be an insulator such as silicon dioxide to provide electrical isolation from other devices. An optical waveguide **346** is shown for transmitting optical information to or from other devices planar to optical coupler **342**. Also shown in this figure is a grating **348** in optical coupler **342** and under fiber **335**.

Grating **348** include a set of apertures in optical coupler **342** that transfer a high percentage of any optical signals from fiber **335** to waveguide **346**. Grating **348** may be about 10 microns wide by 17.1 microns long, thereby matching the mode size of a typical single mode optical fiber. Although seven rows and seven columns of apertures are shown for illustrative purposes, many more such apertures may be utilized in an actual implementation. Each aperture reaches through optical coupler **342** to underlying substrate **344**. Each subwavelength aperture has a width Wsub, a length Lsub, and a depth Dsub (not shown in this Figure). The layout of apertures is measured in periods from the beginning of one aperture to the beginning of the other aperture. A period may also be measured from the ending of one aperture to the ending of the other aperture. Other measures of dispersion may be utilized in alternative embodiments. The period in the same direction as the width of an aperture is Λsub also referred to as the subwavelength period. The period in the same direction as the length of an aperture is ΛG also called the grating period. In this embodiment, the period is about twice the length Lsub. These dimensions are utilized as described below in improving the efficiency and effectiveness of grating **348** in transmitting a light signal from optical fiber **335** to waveguide **346**.

FIG. **3**C is an overhead view of the optical coupling system **350** in which various embodiments may be implemented. Included is an optical coupler **352** with a grating region **358** on a substrate **354** as shown in FIG. **3**B. In this example, grating region **358** has five subwavelength regions **361**, **363**, **365**, **367** and **369** separated by four gap regions **362**, **364**, **366** and **368**. In this embodiment, the length of each subwavelength region Sub (Lsub) is equal to the width of each Gap region (ΛG−Lsub).

FIG. **3**D is a perspective cutaway view of a subwavelength region **390** of the grating area **358** of FIG. **3**C in which various embodiments may be implemented. Shown is a width Wsub and length Lsub of each subwavelength aperture. Also shown is a subwavelength period Λsub. These dimensions are utilized as described below.

Grating **348** and **358** is utilized to diffract the optical signal as desired. By utilizing subwavelength apertures, the incoming optical signal undergoes destructive interference to bend the light to the desired direction. In addition, the use of a subwavelength structure is utilized to adjust the effective refractive index of the grating to a desired index based on the surface layer, trench fill material (which may be air), and the underlying trench layer. According to effective medium theory, a composite medium including two or more different materials interleaved at the subwavelength scale can be approximated as a homogenous medium with an effective refractive index between the two or more materials. As a result, subwavelength period Λsub needs to be small compared to the wavelength of the optical signal inside the waveguide so that the grating area is a subwavelength region. In the example described below, Wsub is set to 80 nm, which is a commercially viable dimension given current semiconductor process technologies. As those technologies improve, smaller sizes may be utilized. In this example, crystalline polysilicon is the surface material, air is the trench fill material with a refractive index of 1, and buried silicon dioxide (BOX) is the underlying trench material with a refractive index of 1.45. By carefully selecting the dimensions and periodicity of the apertures, the effective refractive index can be set at a preferred level. The preferred refractive index is based primarily on the wavelength(s) of the optical signal being transmitted. As noted above, the dimensions and periodicity of the apertures can also be utilized to direct the incoming light signal into the waveguide.

The two refractive indices of particular concern are TE (transverse electric) and TM (transverse magnetic) polarizations. In the following equations and as shown in FIG. **3**A, the x axis is in the direction of the optical fiber signal (roughly orthogonal to the surface of the optical coupler), the y axis is planar to the optical coupler device, perpendicular to the direction of the waveguide, and runs parallel to the widths of the apertures, and the z axis is in the direction of the waveguide, perpendicular to the x and y axes and parallel to the widths of the apertures. Light propagation is in the z direction and the electric field is in the y direction.

$$TE\colon \frac{\sqrt{n_{si}^2 - n_{TE}^2}}{n_{si}^2}\tan\left(\frac{\pi\sqrt{n_{si}^2 - n_{TE}^2}\,(\Lambda_{sub} - W_{sub})}{\lambda}\right) = -\frac{\sqrt{n_{hole}^2 - n_{TE}^2}}{n_{hole}^2}\tan\left(\frac{\pi\sqrt{n_{hole}^2 - n_{TE}^2}\,W_{sub}}{\lambda}\right) \tag{1}$$

$$TM\colon \sqrt{n_{si}^2 - n_{TE}^2}\,\tan\left(\frac{\pi\sqrt{n_{si}^2 - n_{TM}^2}\,(\Lambda_{sub} - W_{sub})}{\lambda}\right) = -\sqrt{n_{hole}^2 - n_{TM}^2}\,\tan\left(\frac{\pi\sqrt{n_{hole}^2 - n_{TM}^2}\,W_{sub}}{\lambda}\right) \tag{2}$$

$$0^{th}\text{ order } TE\colon \frac{1}{n_{TE}^{(0)}} = \left(\frac{f_{sub}}{n_{trench}^2} + \frac{(1 - f_{sub})}{n_{si}^2}\right)^{1/2} \tag{3}$$

$$0^{th}\text{ order } TM\colon n_{TM}^{(0)} = (f_{sub}n_{trench}^2 + (1 - f_{sub})n_{si}^2)^{1/2} \tag{4}$$

$$2^{nd}\text{ order } TE\colon n_{TE}^{(2)} = n_{TE}^{(0)}\left(1 + \frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1 - f_{sub})^2(n_{trench}^2 - n_{si}^2)^2(n_{TM}^{(0)})^2\left(\frac{n_{TE}^{(0)}}{n_{trench}n_{si}}\right)^4\right)^{1/2} \tag{5}$$

-continued

$$2^{nd}\text{ order } TM\colon n_{TM}^{(2)} = n_{TM}^{(0)}\left(1 + \frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1 - f_{sub})^2\left(\frac{n_{trench}^2 - n_{si}^2}{n_{TM}^{(0)}}\right)^2\right)^{1/2} \tag{6}$$

As described below with reference to FIGS. **5**A and **5**B, these equations are utilized to determine the filling factor fsub which is utilized to determine subwavelength period Λsub (i.e. fsub=Wsub/Λsub) optimized for either TE or TM or a balance of both. As described above, trench width Wsub is set to 80 nm based on current process technologies. If much larger sizes are used for the trench width, then higher order equations may be needed for better approximations. The 0th order equations are the zeroth-order approximations of the nsub for the TE and TM polarizations. They are substituted into the second order equations of the nsub for TE and TM polarizations to determine fsub. In these equations and in the example provided herein, λ is the working wavelength of the optical signal, nsi is the refractive index of the surface material (silicon with a value of 3.476 in this example), and ntrench is the refractive index of the trench fill material (air with a value of 1 in the present example). $n^{(2)}$TE and $n^{(2)}$TM are the second order approximations of the nsub for the TE and TM polarizations, which is 2.45 in the present example.

FIG. **4**A is a widthwise cutaway view of the optical coupling device **400** in which various embodiments may be implemented. Although seven columns of apertures are shown for illustrative purposes, many more such apertures may be utilized in an actual implementation. Optical coupling device **400** includes a substrate **410** below an optical coupler **420**. Optical coupler **420** may be a constructed of silicon or similar material. Substrate **410** may continue in the plane of the device and may contain many such devices. Substrate **410** may be an insulator such as silicon dioxide to provide electrical isolation from other devices. Grating **430** is shown with multiple apertures having width Wsub, subwavelength period Λsub, and depth Dsub. Dsub may be the depth of the surface layer used to build the apertures as shown in FIGS. **6**A-**6**E below.

FIG. **4**B is a lengthwise cutaway view of the optical coupling device **450** in which various embodiments may be implemented. Although five rows of apertures are shown for illustrative purposes, many more such apertures may be utilized in an actual implementation. Optical coupling device **450** includes a substrate **460** below an optical coupler **470**. Optical coupler **470** may be a constructed of silicon or similar material. Substrate **460** may continue in the plane of the device and may contain many such devices. Substrate **460** may be an insulator such as silicon dioxide to provide electrical isolation from other devices. Grating **480** is shown with multiple apertures having length Lsub, grating period ΛG and depth Dsub. Waveguide **486** is also shown in this view.

FIG. **5**A is a flow diagram of a process for configuring an optical coupling device in which various embodiments may be implemented. FIG. **5**B is a diagram of a relationship between surface refractive index, grating period and efficiency for a given optical signal wavelength as described with step **520** below.

In a first step **500**, the characteristics of the optical signal to the optical waveguide and the ambient conditions should be obtained, provided or otherwise determined. This includes the primary optical signal wavelength λ signal in nanometers (nm), polarization of that primary optical signal, and the characteristics of the surrounding medium which may exist between the optical cable and the grating. In the case of spread spectrum or other multiple wavelength optical signals, an average or median wavelength may be utilized. In the present example, a wavelength of 1550 nm is used for illustrative purposes. Also in the present example, the surrounding medium is air with an effective refractive index nair of 1. Other ambient conditions may be utilized such as a liquid medium.

In a second step **510**, an optimal grating period ΛG and an optimal refractive index nsub for each row area of apertures may be determined with a known efficiency for the primary optical wavelength and ambient conditions. This determination may be accomplished using a variety of tools including a 2D simulation package CAMFR which is based on the eigenmode expansion technique. This is generated using the primary optical signal wavelength, polarization of that primary optical signal, and the refractive index of the surrounding medium. An example is shown in FIG. **5**B where a gradient based set of efficiencies is shown for an optical wavelength of 1550 nm with a range of grating periods and aperture row area refractive indices. As shown, the optimum subwavelength area refractive index nsub is 2.45 and the optimum grating period ΛG is 0.685 μm with a maximum coupling efficiency of 0.72. Other parameters may be similarly calculated such as the optical fiber should be positioned with an emitting angle θ equal to 9.4 degrees in an air based medium.

In a third step **520**, it is determined whether to optimize for transverse electric polarization (TE) or transverse magnetic polarization (TM) or a balance between those two optimizations. Some applications may perform better if TE is optimized, other applications may perform better if TM is optimized, yet other applications may need a balanced approach. This preference can then be utilized to determine the ideal aperture width Wsub and subwavelength period Λsub. In this example, the grating period ΛG is assumed to be double the length of each aperture length Lsub, resulting in a 50% duty cycle.

If TE is to be optimized, then in step **532** the second order approximation equation of the refractive indices of TE described above is utilized to determine the optimum filling factor fsub. If TM is to be optimized, then in step **534** the second order approximation equation of the refractive indices of TM described above is utilized to determine the optimum filling factor fsub. If a balance between TE and TM is to be optimized, then in step **536** the second order approximation equations of the refractive indices of TE and TM described above are both utilized to determine the optimum filling factor fsub for TE and for TM, with the results averaged or otherwise balanced in step **538**. The results of steps **532**, **534** or **536**-**538** are then utilized in step **540** to complete the design of the optimal optical coupling device given the ambient conditions, input signal characteristics, and the coupling device characteristics. The filling factor may be utilized to directly calculate the optimum aperture width and subwavelength period. The optical coupling device can then be manufactured in step **550** such as described below with reference to FIGS. **6**A-**6**E.

FIG. **5**B is a diagram of identifying the optimum subwavelength area refractive index nsub and the optimum grating period ΛG. This graph is generated using a 2D simulation package CAMFR which is based on the eigenmode expansion technique. This diagram is generated for a single wavelength, which is 1550 nm in this case. Given that wavelength, it is apparent that the optimum subwavelength area refractive index nsub is 2.45 and the optimum grating period ΛG is 0.685 μm with a maximum coupling efficiency of 0.72.

FIG. **6**A through **6**E are widthwise cutaway views of the optical coupling device being manufactured in which various embodiments may be implemented. In FIG. **6**A, an SOI (silicon on insulator) wafer is shown. The silicon (SI) layer **602** may be 250 nanometers in thickness over a buried silicon oxide (BOX) layer **600**. In this example, the depth of the silicon layer sets the subsequent trench depth Dsub. The BOX may be 1 micron thick over an underlying silicon wafer (not shown). Alternative materials and dimensions may be utilized.

In a first step shown in FIG. **6**B, a layer of photoresist **614** is applied over silicon **612** and buried oxide **610**. The photoresist may be poured onto the SOI wafer while the wafer is spinning to obtain an even coat. The photoresist is then exposed with a pattern desired in the underlying silicon. This pattern is based on the dimensions determined utilizing the above described processes including the width and length of trenches and the grating and subwavelength periods. The unexposed photoresist is then removed (or the exposed photoresist is removed depending on the type of photoresist used), generating the photoresist structures **624** shown in FIG. **6**C over silicon **622** and BOX **620**.

As shown in FIG. **6**D, the exposed silicon **632** not covered by photoresist **634** is then etched using a process selective to silicon until the buried oxide **630** is reached. The etching may be timed and/or the buried oxide can act is an etch stop layer. As shown in FIG. **6**E, the photoresist is then removed such as with a solvent selective for photoresist, resulting in the desired nanostructures in silicon **642** over buried oxide **640**.

The description of the present invention has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. The embodiment was chosen and described in order to explain the principles of the invention, the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.

The terminology used herein is for the purpose of describing particular embodiments and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiment was chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. A method of configuring an optical coupling device comprising:

obtaining characteristics of an optical signal and ambient conditions for storage in a memory;

utilizing a processor for identifying an optimum effective subwavelength area refractive index and a grating period for the input signal and ambient characteristics stored in memory; and utilizing the processor for identifying a preferred filling factor for a transverse polarization.

2. The method of claim **1** wherein the transverse polarization is selected from a group consisting of a transverse magnetic polarization, a transverse electric polarization, and a balance of the transverse magnetic polarization and the transverse electric polarization.

3. The method of claim **2** wherein the filling factor is utilized to calculate a subwavelength period for a given aperture width.

4. The method of claim **3** wherein the optical coupling device is manufactured utilizing the identified effective subwavelength area refractive index, the grating period, the aperture width and the subwavelength period.

5. The method of claim **4** wherein the filling factor is identified by utilizing a second order approximation equation of a refractive indices of the transverse polarization.

6. The method of claim **5** wherein the second order approximation equation is selected from a group consisting of

$$n_{TE}^{(2)} = n_{TE}^{(0)}\left(1+\frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1-f_{sub})^2(n_{trench}^2-n_{si}^2)^2(n_{TM}^{(0)})^2\left(\frac{n_{TE}^{(0)}}{n_{trench}n_{si}}\right)^4\right)^{1/2}$$

and

$$n_{TM}^{(2)} = n_{TM}^{(0)}\left(1+\frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1-f_{sub})^2\left(\frac{n_{trench}^2-n_{si}^2}{n_{TM}^{(0)}}\right)^2\right)^{1/2}.$$

7. The method of claim **4** wherein the optical coupling device is manufactured by patterning and etching the grating structures utilizing the identified effective subwavelength area refractive index, the grating period, the aperture width and the subwavelength period.

8. A data processing system for configuring an optical coupling device, the data processing system comprising:

a processor; and

a memory storing program instructions which when executed by the processor execute the steps of:

obtaining characteristics of an optical signal and ambient conditions for storage in the memory;

utilizing the processor for identifying an optimum effective subwavelength area refractive index and a grating period for the input signal and ambient characteristics stored in memory; and

utilizing the processor for identifying a preferred filling factor for a transverse polarization.

9. The data processing system of claim **8** wherein the transverse polarization is selected from a group consisting of a transverse magnetic polarization, a transverse electric polarization, and a balance of the transverse magnetic polarization and the transverse electric polarization.

10. The data processing system of claim **9** wherein the filling factor is utilized to calculate a subwavelength period for a given aperture width.

11. The data processing system of claim **10** wherein the optical coupling device is designed for manufacturing by utilizing the identified effective subwavelength area refractive index, the grating period, the aperture width and the subwavelength period.

12. The data processing system of claim **10** wherein the filling factor is identified by utilizing a second order approximation equation of a refractive indices of the transverse polarization.

13. The data processing system of claim **12** wherein the second order approximation equation is selected from a group consisting of

$$n_{TE}^{(2)} = n_{TE}^{(0)}\left(1+\frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1-f_{sub})^2(n_{trench}^2-n_{si}^2)^2(n_{TM}^{(0)})^2\left(\frac{n_{TE}^{(0)}}{n_{trench}n_{si}}\right)^4\right)^{1/2}$$

and

$$n_{TM}^{(2)} = n_{TM}^{(0)}\left(1+\frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1-f_{sub})^2\left(\frac{n_{trench}^2-n_{si}^2}{n_{TM}^{(0)}}\right)^2\right)^{1/2}.$$

14. The data processing system of claim **11** wherein the optical coupling device is designed for patterning and etching the grating structures utilizing the identified effective subwavelength area refractive index, the grating period, the aperture width and the subwavelength period.

15. An optical coupling device comprising grating structures, wherein the grating structures are configured based on the steps of:

obtaining characteristics of an optical signal and ambient conditions for storage in a memory;

utilizing a processor for identifying an optimum effective subwavelength area refractive index and a grating period for the input signal and ambient characteristics stored in memory; and

utilizing the processor for identifying a preferred filling factor for a transverse polarization.

16. The optical coupling device of claim **15** wherein the transverse polarization is selected from a group consisting of a transverse magnetic polarization, a transverse electric polarization, and a balance of the transverse magnetic polarization and the transverse electric polarization.

17. The optical coupling device of claim **16** wherein the filling factor is utilized to calculate a subwavelength period for a given aperture width.

18. The optical coupling device of claim **17** wherein the optical coupling device is manufactured utilizing the identified effective subwavelength area refractive index, the grating period, the aperture width and the subwavelength period.

19. The optical coupling device of claim **18** wherein the filling factor is identified utilizing a second order approximation equations of a refractive indices of the transverse polarization.

20. The optical coupling device of claim **19** wherein the second order approximation equation is selected from a group consisting of

$$n_{TE}^{(2)} = n_{TE}^{(0)}\left(1+\frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1-f_{sub})^2(n_{trench}^2-n_{si}^2)^2(n_{TM}^{(0)})^2\left(\frac{n_{TE}^{(0)}}{n_{trench}n_{si}}\right)^4\right)^{1/2}$$

and

$$n_{TM}^{(2)} = n_{TM}^{(0)}\left(1+\frac{\pi^2}{3}\left(\frac{\Lambda_{sub}}{\lambda}\right)^2 f_{sub}^2(1-f_{sub})^2\left(\frac{n_{trench}^2-n_{si}^2}{n_{TM}^{(0)}}\right)^2\right)^{1/2}.$$

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