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(54) **HIGH SPEED FREE-SPACE OPTICAL COMMUNICATIONS**

Publication Classification

(75) Inventors: **John R. Joseph**, Albuquerque, NM (US); **Kevin L. Lear**, Fort Collins, CO (US); **David Abell**, Albuquerque, NM (US)

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(73) Assignee: **TRILUMINA CORPORATION**, Reno, NV (US)

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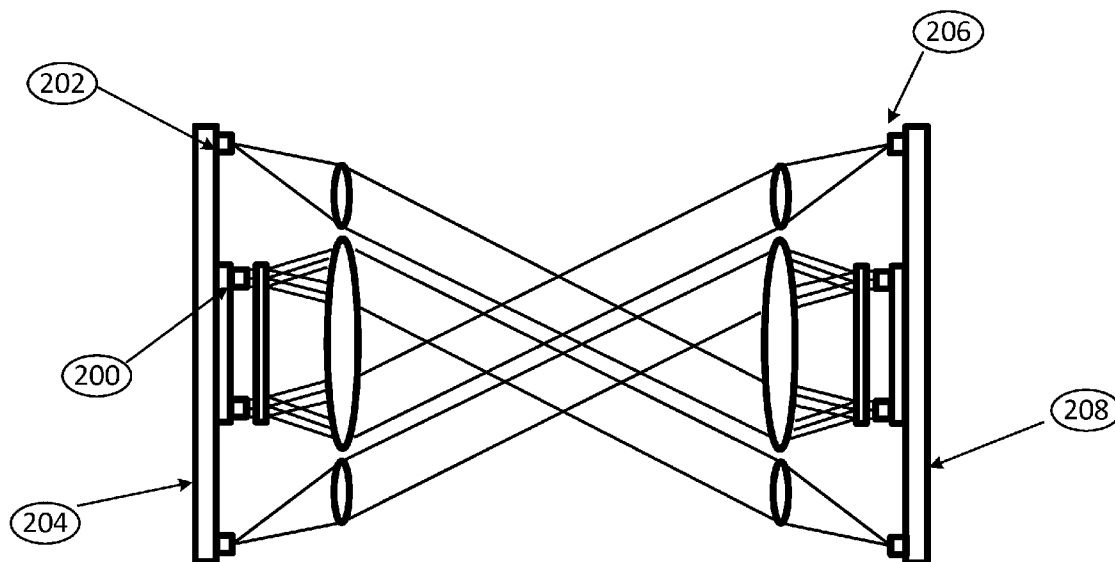
(57) **ABSTRACT**

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/077,769, filed on Mar. 31, 2011, which is a continuation of application No. 12/707,657, filed on Feb. 17, 2010, now Pat. No. 7,949,024, Continuation-in-part of application No. 12/970,880, filed on Dec. 16, 2010.

(60) Provisional application No. 61/528,119, filed on Aug. 26, 2011, provisional application No. 61/671,036, filed on Jul. 12, 2012, provisional application No. 61/153,190, filed on Feb. 17, 2009, provisional application No. 61/288,269, filed on Dec. 19, 2009.

High power, high speed VCSEL arrays are employed in unique configurations of arrays and sub-arrays. Placement of a VCSEL array behind a lens allows spatial separation and directivity. Diffusion may be employed to increase alignment tolerance. Intensity modulation may be performed by operating groups of VCSEL emitters at maximum bias. Optical communications networks with high bandwidth may employ angular, spatial, and/or wavelength multiplexing. A variety of network topologies and bandwidths suitable for the data center may be implemented. Eye safe networks may employ VCSEL emitters may be paired with optical elements to reduce optical power density to eye safe levels.



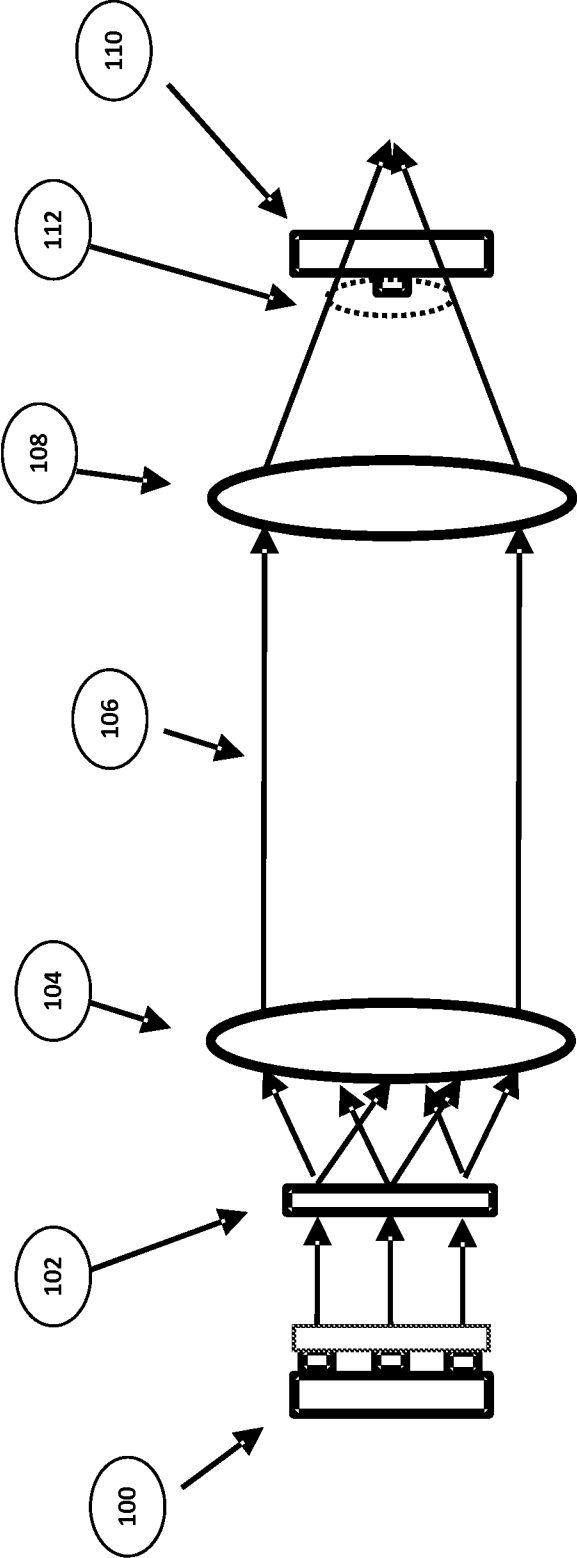


FIG. 1

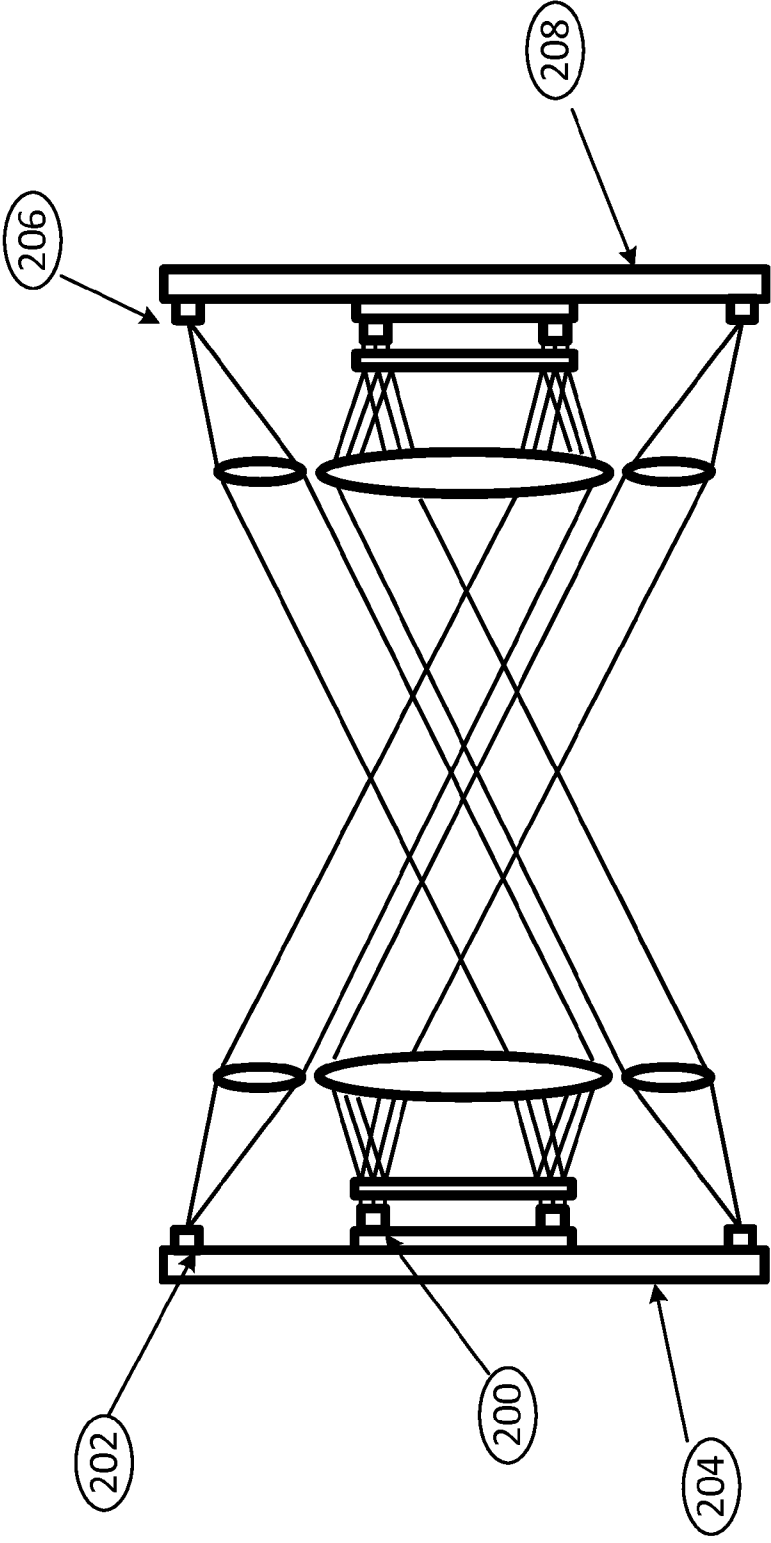


FIG. 2

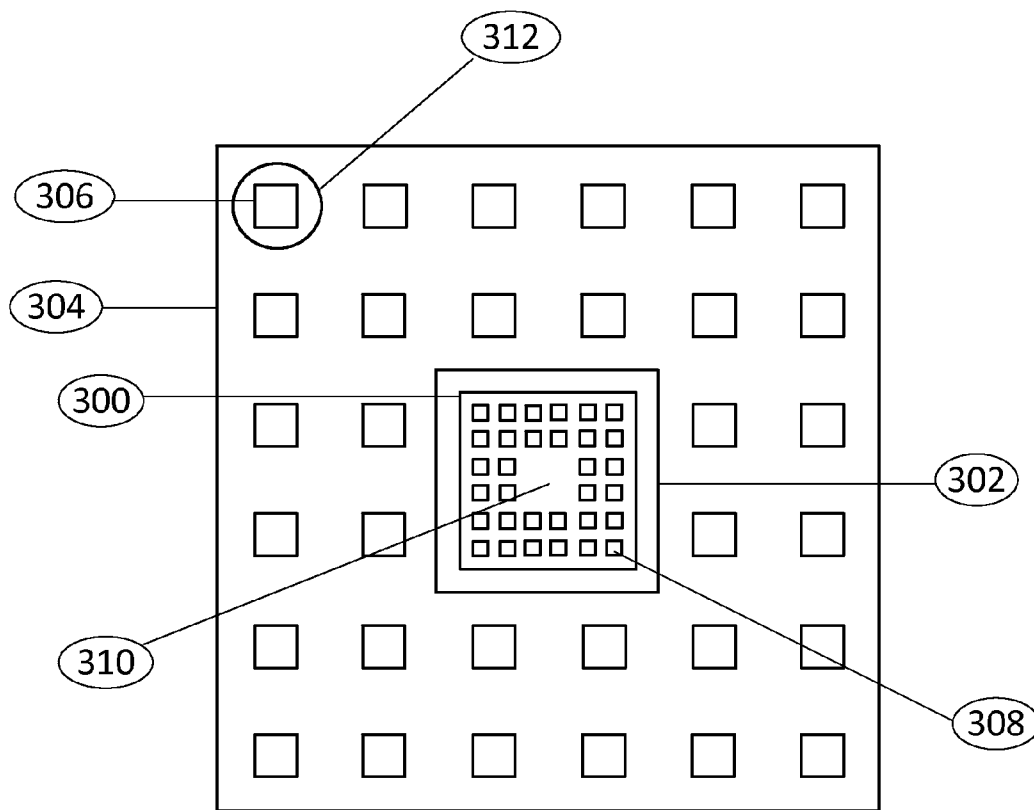


FIG. 3

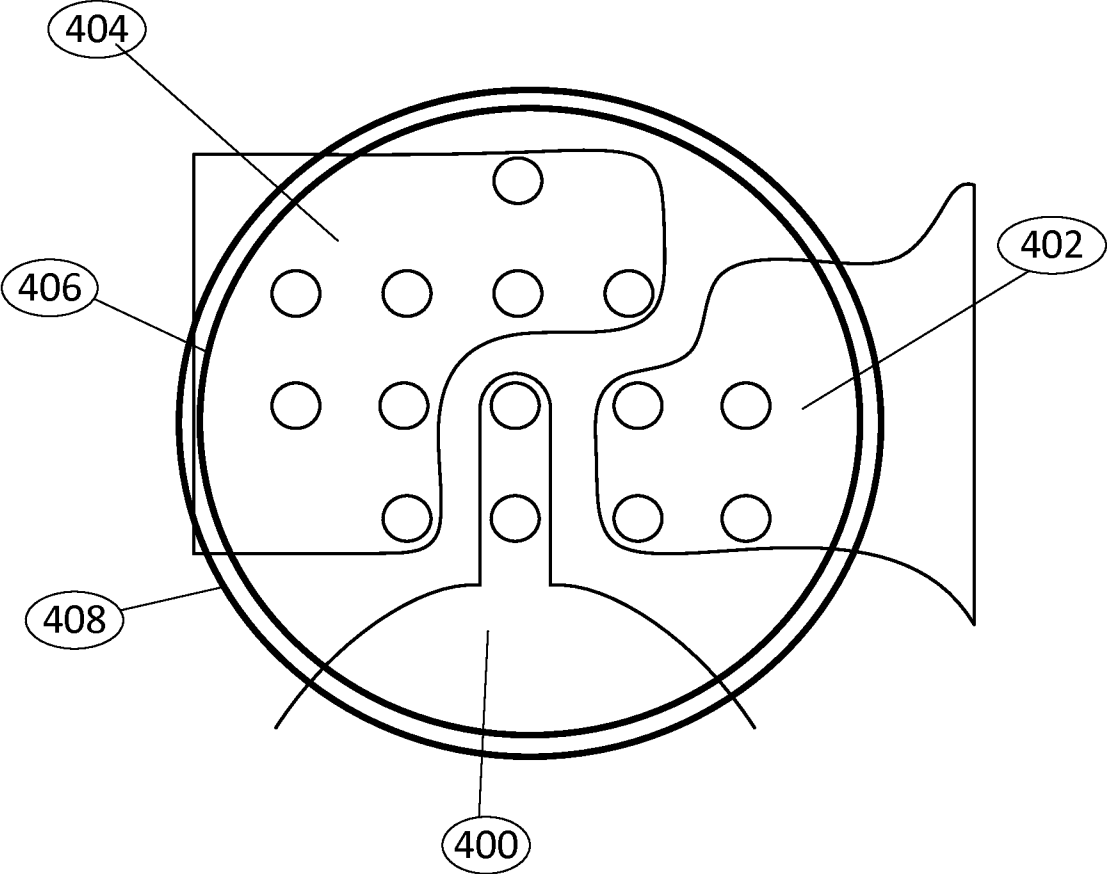


FIG. 4

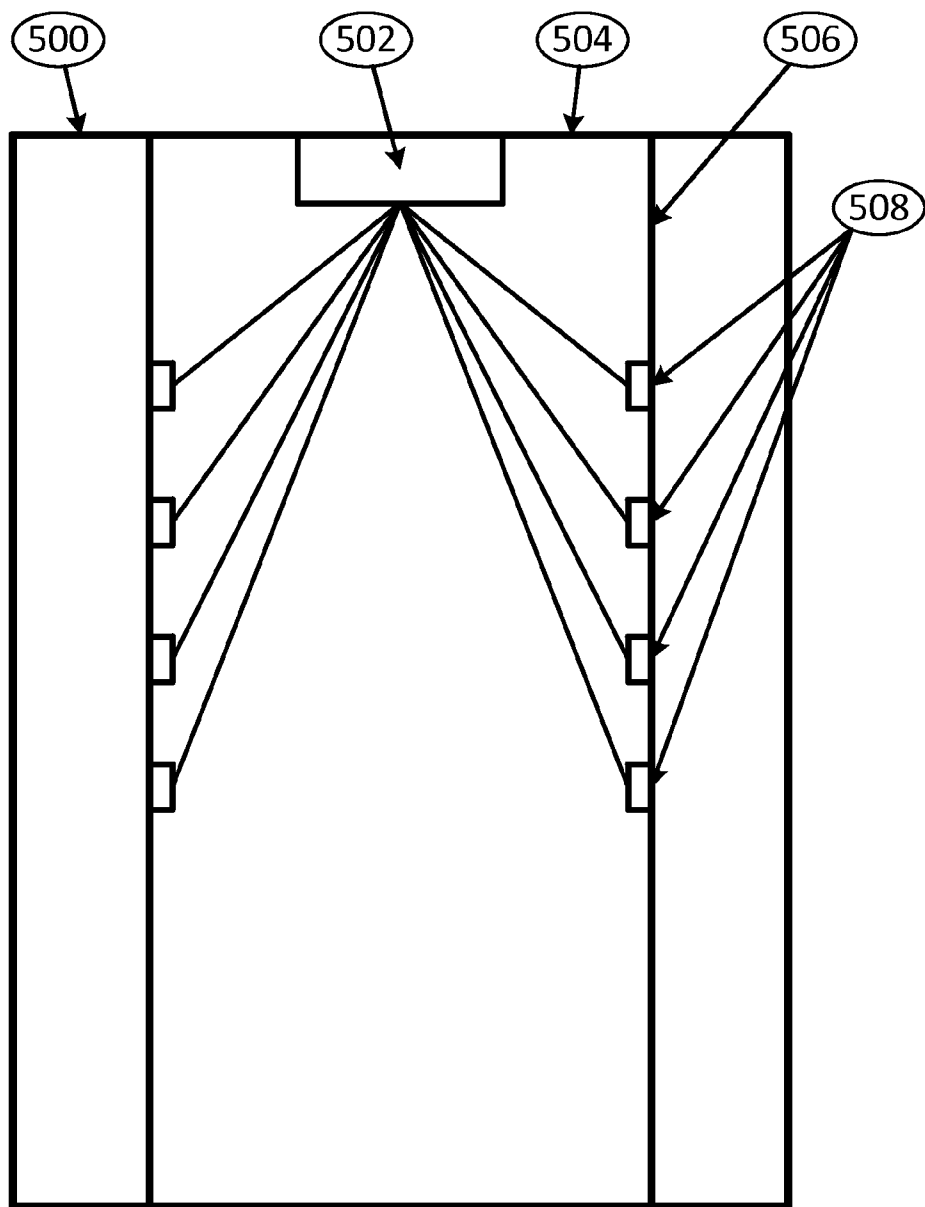


FIG. 5

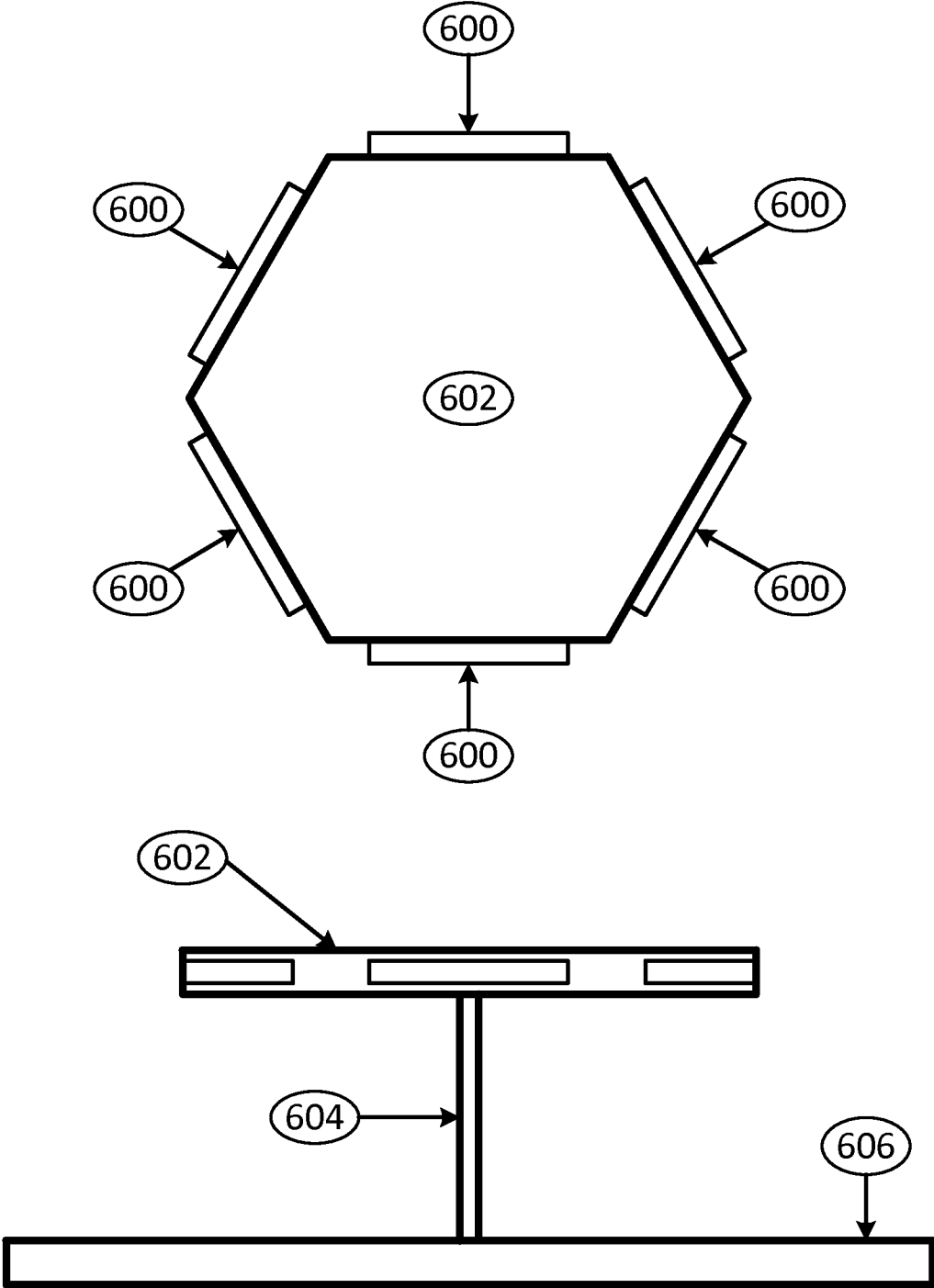


FIG. 6

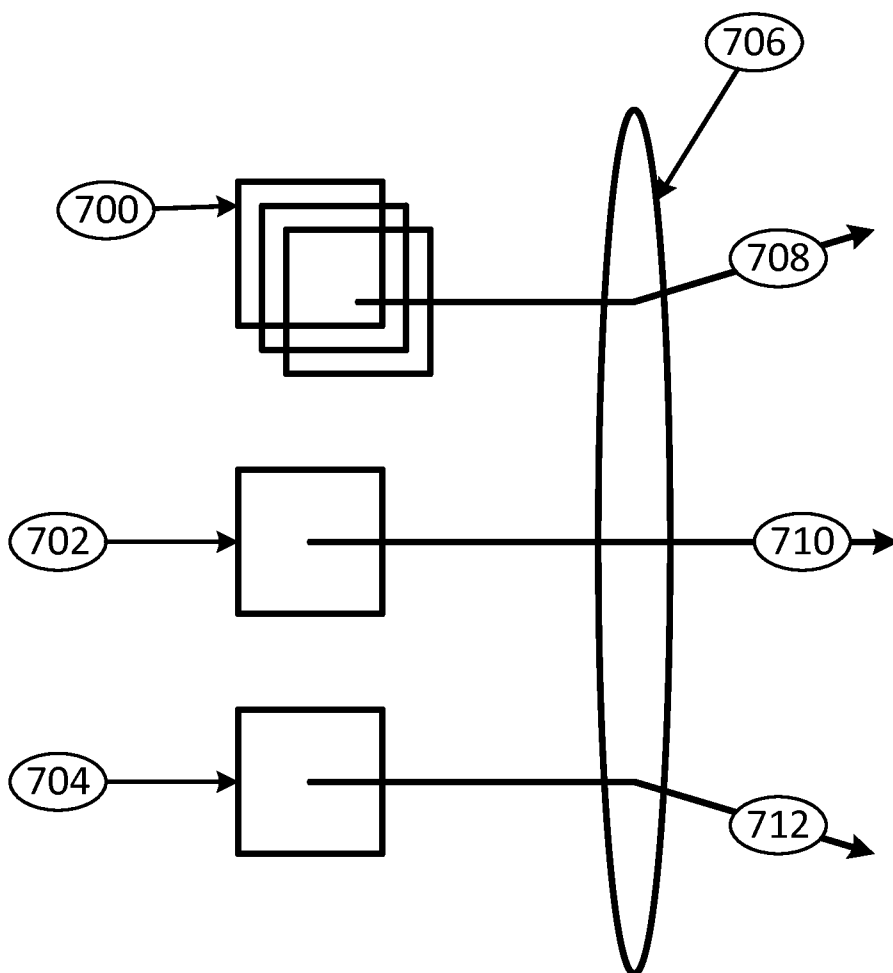


FIG. 7

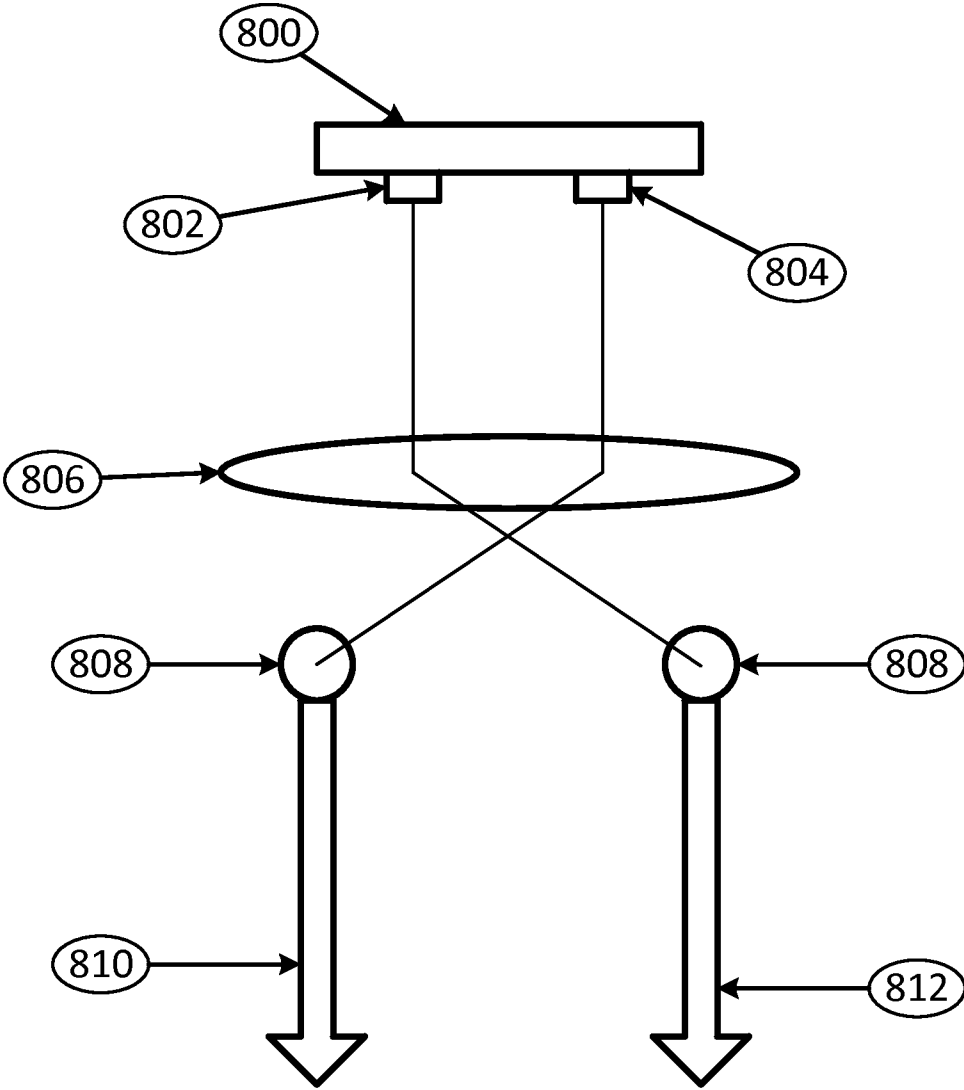


FIG. 8

HIGH SPEED FREE-SPACE OPTICAL COMMUNICATIONS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit under 35 U.S.C. §119(e) of Provisional Application No. 61/528,119, filed Aug. 26, 2011, and of Provisional Application No. 61/671,036, filed Jul. 12, 2012, each of which are incorporated herein by reference in their entirety.

[0002] This application is a continuation-in-part of U.S. patent application Ser. No. 13/077,769, filed Mar. 31, 2011, which is a continuation of U.S. patent application Ser. No. 12/707,657, filed Feb. 17, 2010, now U.S. Pat. No. 7,949,024, issued on May 24, 2011, which claims benefit under 35 U.S.C. §119(e) of Provisional Application No. 61/153,190, filed Feb. 17, 2009; and is a continuation-in-part of U.S. patent application Ser. No. 12/970,880, filed Dec. 16, 2010, which claims benefit under 35 U.S.C. §119(e) of Provisional Application No. 61/288,269, filed Dec. 19, 2009, each of which are incorporated herein by reference in their entirety.

BACKGROUND

[0003] The bandwidth of transmitted data, and the range at which this data can be conveyed in open air has been dependent on technologies that involve slower single or arrayed high power semiconductor laser transmitters or combinations of such transmitters with optical modulators and/or optical amplifiers, or through the use of multiple wavelengths in combination with the previous mentioned components to achieve a high bandwidth rate for free space optical communications over distances farther than a few meters. To date the complexities involved in implementing these technologies have become extremely cost prohibitive especially for a short distance, in meters, for localized systems Available link budget or available power from the emitter is another cost consideration, as is the alignment and detection issues, which become more complicated and expensive. A cost effective wireless optical transmitter with plenty of link budget would be desirable. While vertical-cavity surface-emitting (“VCSEL”) arrays can produce the optical power necessary for the distances mentioned above, and are much more cost effective, existing VCSEL arrays have not been able to produce the extremely high bandwidths (typically associated with single VCSEL devices) that are necessary.

[0004] In short distance optical communications, between adjacent transceivers and transceivers on circuit boards, using a fiber configuration limits alignment of a fiber to a laser aperture. This alignment is typically achieved through the use of mechanically assembled components that add size and cost of manufacturing, and the problem is compounded with multiple fibers. Free space optical designs based on low amounts of power in the link budget means that achievable tolerances require extreme mechanical board to board alignments which add cost with more elaborate mechanical connector designs. Again, single VCSEL devices are best suited for the bandwidth and cost structure, but lack the necessary power and limit alignment to near unachievable tolerances.

SUMMARY

[0005] The related applications illustrate how VCSEL arrays may be fabricated and tested with results that are superior to the state of the art when power and speed are

considered. Due to the greater configuration flexibility in terms of design and packaging possible with VCSEL arrays, unique configurations such as arrays of sub-arrays, multiple wavelength arrays of arrays and patterned shapes can be easily realized allowing the optical path to be easily and quickly scanned without mechanical means, and shaped according to the array configuration or to have multiple possible links increasing the capabilities. The ability to produce cost effective high speed and high power arrays using these technologies creates unique opportunities for cost effective high speed optical wireless communications.

[0006] Also, high speed optical communications between adjacent circuit boards has conventionally been achieved using a fiber optic or multiple fiber transceiver or wavelength-division multiplexing of multiple channels of data into a single optical fiber configuration or a semiconductor laser free space optical transceiver configuration. In either of these configurations, it is necessary to deliver sufficient energy from the emitter to the detector to achieve minimum signal-to-noise ratio at the desired bandwidth. A successful design starts with the available power or link budget, then calculates all of the losses incurred in the system and ends with sufficient power density at the detector. High speed detectors are smaller and thereby require more power density to maintain sufficient signal to noise levels. One of the significant losses in the calculation of the link budget is alignment loss of an emitter to detector. The reliability of the system is highly dependent upon the amount of power available from the emitter to overcome the alignment issues and other system losses.

[0007] Optical communications between adjacent circuit boards offer many benefits including higher bandwidths than what is available with copper connections. A free space optical arrangement would normally be preferred over a fiber system due to the simplicity of components. However, in a free space system, accommodations must be made to account for both translational and angular misalignments between the transmitter and the receiver. In addition, laser safety consideration should be taken into account. Typically free space configurations are limited by low power devices or link budgets that require expensive or precision mechanical connectors or expensive packaging configurations. The embodiments disclosed here employ technology disclosed in the related applications, including commonly-assigned U.S. Pat. No. 7,949,024 to enable high power arrays of VCSEL devices that operate at very high bandwidths. With the added power or link budget available from these laser sources, the loose alignment tolerances enable a dramatic design change which allows small, high speed, cost effective free space simplex or duplex single or parallel channels that increase total bandwidth to levels that have previously been unachievable in a cost effective manner.

[0008] Optical communication may also provide benefits to the data center. Many of the impediments to line of sight communication, such as particulate matter in the atmosphere, are minimal in the data center environment. Greater precision in beam alignment is also achievable. Embodiments of the invention described herein are capable of leveraging these factors to achieve unprecedented bandwidth levels at reasonable cost. Furthermore, the use of optical communications drastically reduces the amount of cabling required in the data center, reducing complexity and maintenance costs.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0009] FIG. 1 depicts a single, one-channel transmitter and receiver pair.
- [0010] FIG. 2 depicts a pair of matching multi-channel transceivers.
- [0011] FIG. 3 depicts a 32-bit emitter chip comprising both emitters and detectors.
- [0012] FIG. 4 depicts an arrangement of sub-clusters useful for intensity modulation.
- [0013] FIG. 5 depicts a free space optical switch in a data center rack.
- [0014] FIG. 6 depicts a structure for mounting a free space optical switch or transceiver above a surface.
- [0015] FIG. 7 depicts an embodiment employing frequency, angular, and spatial multiplexing.
- [0016] FIG. 8 depicts an embodiment of a high speed free space optical switch.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0017] Array Clusters

[0018] An embodiment is disclosed that includes a single, duplex, 1D or 2D array of small clusters of high power and high speed free-space laser beams (such as those described in the related applications) onto a corresponding array of detectors on the receiving side in a symmetric fashion so as to facilitate a mutual pair of inward-facing devices to provide full bi-directional communications. The clusters may be wired in parallel, or may be broken up into binary-weighted sub-groups which are driven individually and in parallel. In either case, the beams from each individual cluster may be blended using a holographic optical diffusing element which spreads the beam bundle to a collimating lens for transfer to the collection lens of each corresponding detector. This also facilitates a board-to-board “daisy chaining” scheme to enable a bus-like data architecture shared by all the boards.

[0019] FIG. 1 depicts a single, one-channel transmitter/receiver pair from the system in FIG. 2 or any similar design. The emitter may be on a chip from an epitaxial grown GaAs wafer which has been processed according to the concept set forth in U.S. Pat. No. 7,949,024, with a cluster of two or more VCSEL elements (100) may be electrically connected in parallel and driven by a single high speed driver. In an embodiment, the beam from each of the elements impinges upon the surface of an optical diffusing element (102) such as a holographic optical diffuser. Such a diffuser has the advantage of providing good optical power uniformity over the resulting beam spread and high transmission efficiency. The diffuse cone from each of the VCSEL elements impinges upon the back of a lens (104), whose focal length equals that of the distance from the diffusing surface to the principal plane of the lens. The beams that emerge from the lens are a combination of the beams from the individual elements, and they are not coherent, which reduces laser speckle effects. The bundle appears to the receiver as a single, semi-collimated disc of light (106). If this disc is of sufficient diameter in comparison to its optical power, then laser safety criteria may more easily be met by treating the bundle as an “extended source”.

[0020] The size of this bundle at the receiver collection lens (108) may under-fill, match, or over-fill the size of the collecting lens, depending upon the amount of translational tolerance desired.

[0021] As this bundle impinges upon the receiver collection lens, it is focused to a small spot behind the surface of the detector (110) so as to form a blur circle (112) at the detector plane. This allows a certain amount of tilt or translational tolerance of the receiver to the optical axis of the transmitter while still delivering sufficient optical power at the detector plane to meet the link budget. A trade-off can thereby be made between angular tolerance and optical power to provide sufficient link budget energy within the blur circle.

[0022] FIG. 2 depicts a pair of matching multi-channel transceivers in a configuration whereby a single GaAs emitter chip (200) is situated between two or more detector/amplifier pair elements (202) on a shared substrate (204). An identical emitter array and detector/amplifier array (206) having a second shared substrate (208) is situated facing, on the optical axis, but at some distance away from the first substrate (204). A symmetric system of transmitters and receivers may thus be constructed to provide simultaneous, multi-channel communications between the two symmetric and facing substrates.

[0023] The emitter chip (200) is comprised of two or more high speed VCSEL clusters, each cluster driven by its own high speed current controlling circuit. As already illustrated in FIG. 1, the transmitter lens is situated after the diffuser such that each different cluster will create its own semi-collimated beam bundle which is angularly shifted from the beam bundles from the other clusters. In this way, each bundle may be directed to its matching receiver collection lens at the periphery of the corresponding receiver substrate. The receiver lens at the periphery of the substrate is offset towards the center of the substrate to accommodate the fact that the transmitter beam is arriving from near the center of the corresponding substrate, and not parallel to the optical axis between the substrates. The scheme may be extended to two dimensions whereby the emitter chip is a 2D array of $m \times n$ clusters, and the detector/amplifier array is a ring of elements surrounding the emitter chip.

[0024] FIG. 3 represents a top view of one of the matching pairs which have a 32 bit configuration. This drawing illustrates the density possible with a transceiver which has 32 clustered emitter sources arrayed on a chip (300) in a pattern that would look like a square donut with the clusters formed around the square area in the middle (310). Many other configurations could be used as described herein. The illustrated design of an embodiment allows a dense, but small emitter chip. The emitter chip would be located in the square area (310), while allowing many detectors and support chips (306) to be located around the perimeter of the structure. The support chips, like transverse impedance amplifiers, could be arrayed on one chip and routed to the detectors in a number of ways that are known to those familiar with the art of chip layouts and integrating hybrid chip layouts. They could also be connected through via holes in the substrate. Passive or active chip cooling techniques could also be used with this configuration.

[0025] FIG. 3 illustrates an embodiment of one transceiver of a matching pair, where an array of parallel driven clustered elements grouped in a configuration (300) that can be easily transferred optically onto a corresponding detector array (304) using the laser source technology, such as that described in U.S. Pat. No. 7,949,024. The individual clusters of elements are themselves arrays of single elements (308), each cluster driven with their own source provide a powerful laser source which overcomes the design problem of link budget and related tolerances by an abundance of power

allowing a large “blur” spot (312) to be imaged across a detector’s position allowing a loose alignment tolerance from board to board. This may enhance plug and play architectures for optical communication between circuit boards.

[0026] Intensity Modulation

[0027] Binary weighted arrays from technology described in commonly assigned US patent Publication No. 2011/0148328 A1, formed within each of the clusters (308) of FIG. 3 may be used to encode additional data into each channel by using digital intensity modulation (Amplitude Shift Keying) for any reasonable number of sub-clusters that could be fit into one cluster and imaged onto the detector. Thus, binary data may be encoded by associating intensity levels with bit positions in the binary data. In one embodiment, the least significant bit (“LSB”) is associated with the lowest intensity level. The number of bits that can effectively be encoded is therefore primarily dependent upon the receiving end having an LSB signal greater than the minimum link budget and the accuracy of the level discrimination circuitry. The diffuser element mentioned above is ideal for distributing the different power levels of each emitter sub-cluster evenly over the detector blur spot.

[0028] VCSELs which have higher frequency responses or become faster as their current bias increases, until approaching power rollover, may enhance intensity modulation. VCSELs prefer to be turned fully on for higher speed capability. Normally, intensity modulation is achieved by using an analog signal level to achieve a different intensity level from the laser and thus lower levels would slow down the entire data transmission system. Turning on different arrays to their highest bias (so as to reduce distortion) and allowing the selected groupings to be used to change the intensity levels, allows very high bandwidths to be achieved using intensity modulation.

[0029] FIG. 4 illustrates an individual cluster grouping that has been divided into three separate binary weighted sub-clusters. The laser output of each sub-cluster increases, in a binary fashion, by either doubling the output of a single element or by adjusting the number of elements to increase the power of the sub-cluster in a binary fashion. Each sub-cluster is controlled by its own driver source which is independent from the other sub-clusters and their drivers. In this manner any combination of bits (sub-clusters) can be controlled and thereby encoded during each clock pulse. Turning on different sub-clusters or combinations thereof during the same pulse timing would represent increased intensity levels which could be identified by a level discrimination circuit as different encoding levels. In this case group (400) has 2 VCSEL emitters, group (402) has 4 VCSEL emitters and group (404) has 8 VCSEL emitters. It is assumed that each of the emitters in this example has close to the same power output as its neighbors. Holographic optical element (406) distributes the hotspots to a more intensity uniform mixed beam and lens (408) semi-collimates the output of whichever groups of arrays are turned on in a single pulse.

[0030] As the varying groups are turned on the following data information can be directed through beam intensity levels provided the detector has the dynamic range to detect differences between the least significant bit (LSB) level and the intensity level of the most significant bit (MSB):

[0031] 000—No groups on during clock pulse

[0032] 001—only group (400) is turned on during clock pulse

[0033] 010—only group (402) is turned on during clock pulse

[0034] 011—group (400) and (402) are turned on during same clock pulse

[0035] 100—only group (404) is turned on during clock pulse

[0036] 101—group (400) and (404) are turned on during same clock pulse

[0037] 110—group (402) and (404) are turned on during same clock pulse

[0038] 111—group (400), (402) and (404) are turned on during same clock pulse

[0039] These configurations allow eight separate data codes to be relayed with one pulse. The preferred embodiment could use this intensity modulation technology but it is not necessary. Intensity modulation may also be achieved, for example, without defining groups or by having a one-to-one relationship between groups and emitters.

[0040] An additional embodiment would employ wavelength-division multiplexing or dense wavelength-division multiplexing, with each particular wavelength having bit string information encoded on each of the respective pulses for that wavelength, or other optical multiplexing schemes, such as orthogonal frequency division multiplexing, where a number of closely spaced orthogonal sub-carrier signals are used to carry data. A device of this nature is capable of an extremely high data transfer rate. Furthermore, frequency doubling is not required in this embodiment. Frequency adding may be employed to achieve longer, eye-safe wavelengths, which is an important factor when high powered laser propagation is employed.

[0041] In another embodiment, any number of wavelengths or beams produced by any number of light sources and/or emitter chips may be combined by one or more optical elements to form a highly resolved data pulse. Such a device is capable of potentially unlimited bit information capacity, subject only to the size, focal length, and distance of the combining lens and the number of subgroups that can be defined according to the limits of the dynamic range of detection.

[0042] Beam Steering

[0043] In an embodiment, an array or cluster of photonic elements behind a lens, such that beams emitted from the photonic elements strike the lens at varying positions, providing directivity. Beam steering may be achieved by selectively activating an element of the array. This allows for non-mechanical optical alignment, thus reducing or eliminating excessive gimbals movement, saving energy and increasing reliability. Beam scanning may also be achieved through use of this technique. Both one-dimensional and two-dimensional directivity may be achieved by the use of one-dimensional or two-dimensional arrays, respectively. In addition, 360° coverage may be achieved by employing multiple sectors, e.g. a hexagonal, spherical, or other three-dimensional arrangement of outward-facing arrays.

[0044] Optical Switching in a Data Center Environment

[0045] Additional embodiments allow for optical switching applications that employ an array of photonic elements behind a lens. Narrow beams may be preferred in this embodiment. In a data center rack, an optical switch employing this technique may be placed such that narrow beams emitted from the switch may reach defined positions within the rack. For example, the switch may employ a multiple lens array and be placed at the top of the rack, as seen in FIG. 5. In one

embodiment, equipment rack (500) may contain in its interior optical switch (502) mounted to surface (504), which may be the ceiling of the rack. Detectors (508) may be mounted to surface (506), which may be interior to the rack or a wall of the rack. Optical switch (502) and detectors (508) are placed such that optical communications between the switch and the detectors are not disturbed, for example by maintaining line of sight between the optical switch (502) and the detectors (508). This arrangement allows for precise data shower beams to reach server connections at defined positions within the rack, enabling a cable free rack. While a ceiling arrangement is illustrated in FIG. 5, the optical switch (502) could be mounted on the floor of the rack or anywhere in-between the floor and the ceiling, depending on the configuration of the rack and what portion of the rack provided the clearest line of sight for the beams.

[0046] Other embodiments allow for various network topologies, employing a wide variety of link geometries such as star, daisy chain, ring, or mesh. Various factors such as the arrangement of racks, airflow, and electrical cabling may create impediments to line of sight, but these impediments may be overcome by selecting suitable link geometry. The appropriate geometry may involve not only the network topology, but also correct positioning in both the horizontal and vertical dimensions. For example, the device pictured in FIG. 6 may be employed to position the photonic array a suitable distance above a rack. Optical switches or transceivers (600) may be mounted to a multi-sided structure (602), which is shown having six sides, but could be configured to have many different configurations with many different numbers of side. The mounting system may support alignment or reorientation of the optical switches or transceivers (600). For example, as shown in the lower portion of FIG. 6, the multi-sided structure (602), shown from a side perspective, may be connected to rack (606) by support structure (604), which may allow for rotation or height adjustment. Further the optical switch (600) may be formed from arrays of sub-arrays with a lens positioned in front of the groupings of sub-arrays in order to steer a beam emitting from switch (600) to a specific position where the detection might be located. This may allow another degree of freedom and allow automatic alignment of beams. These subgroups of arrays in combination with the correct lens design may cover a small area in which automated beam alignment may take place by a scanning and receiving scheme.

[0047] Use of embodiments within the data center allow for improved link budget. More precise alignment of the beams allows for a narrower field of view and relaxed power requirements, which in turn allows for higher bandwidth. When used within the data center, embodiments are capable of achieving at least gigabit/second throughput on the free space optical communication network.

[0048] On a macro scale, not all frequencies propagate well in the atmosphere. Suspended particulate matter, such as fog, dust, rain, or snow, may also impeded light-wave propagation. However, in a data center most frequencies propagate well enough and particulate matter is not usually an issue.

[0049] High aggregate bandwidth, 40 Gb/s or higher, may be achieved through multiplexing. Wavelength-division multiplexing allows for multiple light wavelengths to be placed on the same optical path. Where the source configuration is overlaid, greater power density results. The source configuration may also be tiled, allowing for angular separation. An embodiment may employ frequency multiplexing or spatial

and angular multiplexing with a single wavelength, as depicted in FIG. 7. For example, stacked emitter (700) may emit laser output at multiple frequencies, striking the surface of lens (706) and following optical path (708). Non-stacked emitters (702) and (704) may emit frequencies of the same or different wavelengths, and their output strikes lens (706) and follows optical paths (710) and (712), respectively. The beam size determines both spatial channel density and angular resolution.

[0050] High Speed High Power Arrays for Optical Switching

[0051] Arrays of VCSEL devices may be used in a high speed switching matrix. Information may be fed to the switch by a single source such as a 100 Gb/s fiber connection. Each packet of information that needs to be routed is separated by a standard routing chip that routes packets to the appropriate output channel.

[0052] The signal from the output channel may be amplified by a high speed current driver which is connected to a single VCSEL device, or an array of VCSEL devices. Each of these, in turn, is part of a larger array, the size of which defines how many channels are available in the overall switching network.

[0053] The output of the laser devices are separated by a controlled distance that is imaged through an optical element onto a pattern of optical elements, such as lenses, arrays of lenses, or optical fibers. The signal of each sub-element is then injected into that single optical or fiber channel. Additional optical elements that could be deployed within the path of a laser beam for a variety of purposes include diffusers, mirrors, and MEMS devices, to name a few.

[0054] The optical or fiber channels also form an array. The output of this array may be handled in at least two ways. First, it may be directed onto an array of detectors, with each detector signal being converted back into an optical signal and injected into a fiber. The fiber may go to an optical plug such as a single fiber plug, or any other type of optical termination. Second, the output of the optical switching array may be injected directly into an optical element or fiber.

[0055] In order to end up with a detectable signal, the link budget of the configuration must be analyzed. In many cases there is insufficient power at the start of the system. Extra power will enhance the signal quality and improve the bit error rate. It may therefore be desirable to operate each sub-element at as high a power level as practical.

[0056] An embodiment is depicted in FIG. 8. A number of VCSEL arrays (802), (804) may be mounted to a surface (800). Output from the VCSEL array (802) passes through lens (806), striking ball lens (808), which may be coupled to a channel (812), which may be an optical fiber. Likewise, output from the VCSEL array (804) passes through lens (806), striking ball lens (808), which may be coupled to a different channel (810). The lines depicted in FIG. 8 representing the output do not represent ray tracing, but rather only a positional imaging relationship.

[0057] Eye Safe Optical Networks for Home and Office

[0058] Numerous applications may make use of the herein disclosed form of free space optical communications. For example, using a transmitter to spread power density over a large area in which the power density is eye safe, one or more emitters/receivers may be embedded in a table top, with a light signal coming up to a counter or surface with a protective clear cover so that mobile devices which have an emitter/receiver on or embedded in the device, may be placed on top

of a table and automatically linked to a 1 G to 10 G data source. Numerous other physical configurations are possible involving emitters/receivers being placed in other locations in or around a surface in the room for the same purpose. For example, a laser emitter cluster may emit a laser beam to an optical element shaped as a clear planar surface having a first side and a second side, where the first side receives the laser beam and spread an output of the laser beam over an area of the second side sufficient to reduce a power density of the laser beam to an eye safe level.

[0059] Embodiments ease this type of operation because no aligning is necessary due to the wide signal coverage area. In addition, there are no hardwired connections to get lost, mangled or stolen. Public access networks of this type are much easier without cables. Transmitters could use THUNDERBOLT technology from INTEL or other protocols. These transmitters need more power for larger area of transmission.

[0060] Free-space optical communications over a distance greater than a meter requires a limited optical power density for eye safe operation, in combination with wider area coverage for ease of reception positioning. These requirements have limited the devices capable of offering the high-power and high-speed required for a wider field of use.

[0061] With the sufficient bandwidth and power density enabled by the high-powered, high-speed device offering a wide field of use for the optical signal, a single link may transmit data over multiple channels or may serve many users simultaneously. An array of sub-grouped arrays behind a lens may be switched so that separate beams can be positioned relative to separate areas. Detectors arrays, also called Free-Space Optical MIMO (Multiple Input-Multiple Output) detectors, may be sequenced to identify where signals need to be sent and send signals to those specific areas. Multiple sub-grouped arrays may be functional in any one time sequence, which allows simultaneous communication links to multiple users. Another embodiment for multiple users may employ wavelength division multiplexing by the same MIMO detectors scheme as described above, but with filtered inputs sensitive to multiple wavelengths, and the ability to sense and respond using multiple channels at different wavelengths for both input and output.

[0062] One or more transmitters may be connected to a data source such as a fiber optic cable, a high speed Ethernet cable, or a video source.

[0063] A transmitter may consist of a signal input interface, the packaged VCSEL array, VCSEL driver, and control and amplification electronics, and may also include receiver components and electronics making a transceiver and appropriate beam-shaping optics, all in a common housing. Other components may include an optical component for spreading the optical power density to eye safe levels and a lens for controlling beam diameter and dispersion of the beam in the free space area.

[0064] The transmitter and receiver housing may be pointed towards each other using a simple plastic molded eyeball type socket scheme. The transmitter or transceiver may be pointed toward the receiver or transceiver by an adjustable gooseneck lamp type configuration. The transmitter and receiver may each operate from a simple low voltage DC power supply or even batteries. The transmitter/transceiver may be installed in conjunction with other ceiling-resident utilities such as lighting, safety/security sensors, video cameras and security claxons.

[0065] The VCSEL array may be operated as a group (ganged), or as an addressable array where one or more sub-arrays, each of one or more elements, may be independently signal-driven and moved across the total array positionally.

[0066] The transmitter may operate in "broadcast" mode delivering a wide beam of data to one or more receivers.

[0067] The transmitter may operate in "beaming" mode delivering a narrow beam to one or more receivers.

[0068] The transmitter may operate in "panning" mode where sub-arrays are operated in sequence across the VCSEL array which translates into an angular motion in free-space.

[0069] The system may be configured as a simplex (one-directional) link, or as a full duplex (bi-directional) link. In the latter case, there is a VCSEL array and one or more detectors at each end of the optical link.

[0070] When detector arrays are used, the detector array or sub-array having the strongest signal may be selected as indicating the nearest transmitter for preferential attention, for "hand-off" to a neighboring transmitter, or to accommodate moderate angular misalignments of the receiving optics away from the desired transmitter.

[0071] Transmitters may be placed in a ceiling of an office, with each one spaced at a distance such that they have sufficient coverage at the receiver without excessive overlap of signal.

[0072] Transmitters may be placed centrally on a vertical support, such as a light pole, with each transmitter covering its own angular sector of space.

[0073] The receiver may consist of a light collecting device, a detector, amplifying electronics and a suitable output interface.

[0074] The light collecting device may be an imaging lens or a non-imaging device such as a cylindrical parabolic concentrator.

[0075] At the receiving detector, the data may be conveyed to a local data transport scheme such as fiber optic, Ethernet, digital video cable or even wireless such as Wi-Fi.

[0076] The receiver may also be incorporated directly into a digital switch or router which distributes the ultra-high bandwidth to multiple local users over cable or wireless.

[0077] The receiver may be integrated directly to the component needing the high bandwidth link.

[0078] Because of the likely asymmetry of the bandwidth required for the downlink versus the uplink, alternative cable or wireless uplinks may be used such as Wi-Fi, BPL, Ethernet, etc.

[0079] An optical filter for the transmitter wavelength may be used at the receiving end to suppress all other wavelengths other than that of the transmitter needed. Multiple wavelength links in a single transmitter may be used.

[0080] Polarized VCSEL arrays may be used in conjunction with polarized filters on the receivers to help eliminate stray reflection signal interference.

[0081] Optical limiting path blinders at the receiver may eliminate stray reflective signals coming in at different angles other than the incident signal.

[0082] Multiple transmitters or transceivers may be used from different locations allowing an triangulational positioning grid for best signal reception or to prevent signal blackout from moving objects.

[0083] Window filters may be used for securing data from leaving building. Transmitters or transceivers may be mounted on walls, floors, ceilings or objects. Transmitters or transceivers may be mounted in attics crawl spaces or hard to

access point to point areas. Transmitters or transceivers may be mounted in pipes. Transmitters or transceivers may be mounted in chimneys.

Additional Embodiments

[0084] Numerous additional embodiments are possible. For example, each matching pair of a transceiver anywhere from one to thousands of pairs may use this technology in any number of layout configurations.

[0085] Clusters of elements may be driven as a single channel or configured for intensity modulation of each transceiver channel.

[0086] A bottom emitting array is disclosed in U.S. Pat. No. 7,949,024. However, a bottom emitting array in a flip-chip configuration or a top emitting array or grouping of top emitting arrays may be used for the multi-element emitter devices.

[0087] A single duplex transceiver may be used for board to board free space optical communications using arrayed VCSEL technology mentioned in U.S. Pat. No. 7,949,024.

[0088] A 2D pattern of almost any shape may be formed instead of merely a square or rectangular pattern which might function better using round optical elements.

[0089] A 1D array with any number of clusters or emitters could be used in a configuration other than single or 2D.

[0090] Any number of patterns could be used to form the clusters and to image onto the same pattern of arrays.

[0091] The 1D or 2D arrays could be used as a backplane to select which channel will receive the data pulse by selecting a different emitter or emitters to transfer the data to those select channels. When data needs to be sent to a specific channel the appropriate emitter would be chosen which is already in alignment to that channel through the imaging or projecting lens in front of the whole array. Embodiments could also be used at longer distances for high speed data communications applications with the appropriate imaging optics

[0092] Emitter arrays mentioned above in FIG. 3 (300) could be formed from the same high speed and high power technology or, as noted above, flip chipped to a substrate instead of designed onto the substrate.

[0093] Flipped chipped emitters could be at a different wavelengths allowing WDM capability for emitters and appropriate filtering of wavelengths for detectors.

[0094] High power beams could be spread over a larger receiving area or overlapping with other emitter beams onto an area that may have multiple detectors. Filters covering the detectors could be used in conjunction with multiple wavelength emitter chips to separate the signals of those overlapping beams from different wavelength emitter clusters.

[0095] Transmitters or transceivers may be used for high speed long haul applications.

[0096] Transmitters or transceivers may be used between satellites.

[0097] Transmitters or transceivers may be mounted on telephone poles or rooftops of buildings.

[0098] Transmitters or transceivers may be mounted on vertical poles for better transmission angles.

[0099] The receiver portion of a transceiver may have a photovoltaic or "solar cell" situated around the detector in able to recover all optical power possible, or at least excess laser energy, when the bundle of laser beams is configured to over-fill the collection lenses and detectors in an area so to achieve easier alignments.

[0100] The photovoltaic device mentioned above may be a source of power which is transmitted optically from a base station or device in order to transmit power and/or data communications.

[0101] In one embodiment, linear arrays with any number of rows may be employed for data transmission. Any number or all of the rows may be simultaneously on, even if the pulses have the same or similar wavelength. The output position of each row, in relation to the other rows, adds a dimensional element to wavelength-division multiplexing or dense wavelength division multiplexing.

[0102] In another embodiment, a one-dimensional array is used as to produce a single wavelength pulse, which is combined with other sources of the same or different wavelengths. The combined wavelength's output pulse intensity is scanned in a vertical and horizontal manner, enabling data transmission.

[0103] In another embodiment, the speed and data rate of VCSEL arrays can be increased by employing flip chip technology and a design for high-speed arrays with a waveguide being formed around each sub-array or element, as described in U.S. Pat. No. 7,949,024.

What is claimed:

1. An optical communications device for free-space optical communication, comprising:

one or more clusters of laser emitters configured to emit one or more laser beams;

an optical diffusing element configured to receive the one or more laser beams and output a diffuse cone for each of the one or more laser beams;

one or more collimating lenses configured to combine the diffuse cone into a bundle of laser beams;

one or more collection lenses configured to receive and focus the bundle of laser beams into a focused bundle of laser beams; and

one or more clusters of laser detectors configured to receive the focused bundle of laser beams from the one or more collection lenses, wherein each cluster of detectors is configured to be optically coupled with a corresponding cluster of emitters by the one or more collimating lenses and the one or more collection lenses.

2. The optical communications device of claim 1, wherein the bundle of laser beams is configured to over-fill or under-fill the one or more collection lenses based on a desired amount of translational tolerance.

3. The optical communications device of claim 2, further comprising a photovoltaic device configured to surround each laser detector among the one or more clusters of laser detectors to collect excess laser energy when the bundle of laser beams is configured to over-fill the one or more collection lenses.

4. The optical communications device of claim 1, wherein bundle of laser beams is a combination of the one or more laser beams, and wherein the one or more laser beams in the combination is not coherent.

5. The optical communications device of claim 1, wherein the one or more collection lenses is configured to focus the bundle of laser beams at a focal point behind a surface of the one or more clusters of detectors so the focused bundle of laser beams forms a blur circle at the surface of the one or more clusters of detectors.

6. The optical communications device of claim 5, wherein the focal point is based on a desired translational tolerance and a desired optical power of the focused bundle of laser beams.

7. The optical communications device of claim 1, further comprising one or more drivers, and wherein each of the one or more clusters of laser emitters include two or more VCSEL elements configured to be electrically connected in parallel and driven by a single driver among the one or more drivers.

8. The optical communications device of claim 1, wherein: the one or more clusters of laser emitters are centrally located on a surface and are driven by an independent controlling circuit; and

the one or more clusters of laser detectors are located distally to the one or more clusters of laser emitters.

9. The optical communications device of claim 8, wherein the one or more clusters of laser emitters are arranged in a linear array.

10. The optical communications device of claim 8, wherein the one or more clusters of laser emitters are arranged in a two-dimensional array and the one or more clusters of laser detectors form a perimeter around the plurality of emitters.

11. The optical communications system of claim 1, wherein the one or more collection lenses are configured to blur the focused bundle of laser beams based on a desired alignment tolerance or link budget.

12. A system for the optical free-space transmission of a string of binary data, the system comprising:

a first cluster of laser emitters associated with a first output level;

a second cluster of laser emitters associated with a second output level, the second cluster of laser emitters comprising a greater number of laser emitters than the first cluster of laser emitters;

circuitry configured to determine a first activation state for the first cluster of laser emitters during a clock pulse, the first activation state based on a binary value at a first bit position in the string of binary data; and

circuitry configured to determine a second activation state for the second emitter cluster during the clock pulse, the second activation state based on a binary value at a second bit position in the string of binary data.

13. The system of claim 12, wherein the first cluster of laser emitters and the second cluster of laser emitters are configured to operate so as to reduce distortion.

14. The system of claim 12, wherein the second cluster of laser emitters has twice the number of laser emitters as the first cluster of laser emitters.

15. The system in claim 10, further comprising one or more additional clusters of laser emitters, wherein each additional cluster of laser emitters among the one or more additional clusters of laser emitters has twice the number of laser emitters as a most significant binary group of laser emitters from a prior cluster of laser emitters.

16. The system of claim 10, further comprising a holographic optical element and lens configured to receive the output of the first cluster of laser emitters and the second cluster of laser emitters and form a uniform intensity beam.

17. A system for the optical free-space transmission of a string of binary data, the system comprising:

a first cluster of laser emitters associated with a first output wavelength;

a second cluster of laser emitters associated with a second output wavelength;

circuitry configured to determine a first activation state for the first cluster of laser emitters during a clock pulse, the first activation state based on a binary value at a first bit position in the string of binary data; and

circuitry for configured to determine a second activation state for the second cluster of laser emitters during the clock pulse, the second activation state based on a binary value at the second bit position in the string of binary data;

18. The system of claim 14, further comprising a holographic optical element and lens configured to receive output from the first cluster of laser emitters and the second cluster of laser emitters and form a combined beam.

19. The system of claim 14, wherein the first output wavelength and the second output wavelength are adjusted to an eye safe wavelength.

20. The system in claim 17, further comprising one or more additional clusters of laser emitters, wherein each additional cluster of laser emitters among the one or more additional clusters of laser emitters is associated with an additional output wavelength and each additional cluster of laser emitters has twice the number of laser emitters as a most significant binary group of laser emitters from a prior cluster of laser emitters.

21. An optical communications device for free-space optical communications capable of non-mechanical beam directivity, the device comprising:

a lens;

a plurality of laser emitters positioned behind a lens, each of the plurality of laser emitters configured to emit a laser beam travelling a distinct optical path through the lens; and

circuitry configured to activate one of the plurality of laser emitters based on a desired optical path for the laser beam.

22. The device of claim 21, wherein the plurality of laser emitters are configured in a linear array.

23. The device of claim 21, wherein the plurality of laser emitters are configured in a two-dimensional array.

24. The device of claim 21, wherein the plurality of laser emitters are configured in a three-dimensional arrangement of outward-facing arrays.

25. A free space optical communications network comprising:

a first surface;

a cluster of laser detectors connected to the first surface;

a second surface; and

an optical switch connected to the second surface, the optical switch comprising:

a cluster of laser emitters configured to emit a laser beam;

one or more optical elements configured to receive the laser beam and output a beam striking the cluster of laser detectors; and

circuitry configured to transmit information to the cluster of laser detectors by driving the cluster of laser emitters.

26. The optical communications network of claim 25, wherein the first and second surfaces are interior to an equipment rack.

27. The optical communications network of claim 25, wherein the first surface is located on a first equipment rack and the second surface is located on a second equipment rack.

28. The optical communications network of claim 25, wherein the first surface is located above an equipment rack.

29. A free space optical communications network comprising:

- a first surface;
- a first cluster of laser detectors connected to the first surface;
- a second surface; and
- a transceiver connected to the second surface, the transceiver comprising:
 - a cluster of laser emitters configured to emit a laser beam;
 - a second cluster of laser detectors;
 - one or more optical elements configured to receive the laser beam and output a beam striking the first cluster of laser detectors; and
 - circuitry configured to transmit information to the first cluster of laser detectors by driving the cluster of laser emitters.

30. The optical communications network of claim 29, wherein the second surface is located above an equipment rack.

31. An eye safe free space optical communications system comprising:

- a laser emitter cluster emitting a laser beam carrying data; and
- an optical element shaped as a clear planar surface having a first side and a second side, the optical element configured to receive the laser beam at the first side and spread an output of the laser beam over an area of the second side sufficient to reduce a power density of the laser beam to an eye safe level.

32. The optical communications system of claim 31, wherein the optical element is located on or in a table top.

33. The optical communications system of claim 31, wherein the output from the optical element delivers a wide beam of data to one or more receivers.

34. The optical communications system of claim 31, wherein the optical element is mounted on or in a wall or ceiling.

35. The optical communications system of claim 31, further comprising an optical filter coupled to a receiver.

36. The optical communication system of claim 35, wherein the emitter is polarized and the optical filter is polarized.

37. The optical communication system of claim 31, further comprising a window filter blocking transmission of wavelengths associated with the emitter.

38. The optical communication system of claim 30, further comprising:

- a first detector associated with a first channel of information and a first signal strength;
- a second detector associated with a second channel of information and a second signal strength; and
- circuitry configured to select the first channel of information or the second channel of information based on the first signal strength and the second signal strength.

39. An eye safe free space optical communications system comprising:

a laser emitter cluster emitting a laser beam carrying data; a transmitter for receiving the laser beam and creating a spread laser beam that is spread over an area sufficient to reduce a power density of the laser beam to an eye safe level; and

a protective cover for placement over the transmitter.

40. The optical communications system of claim 39, wherein the protective element is located on or in a table top.

41. The optical communications system of claim 39, further comprising one or more receivers for receiving the spread laser beam, wherein the spread laser beam delivers a wide beam of data to the one or more receivers.

42. The optical communications system of claim 39, wherein the protective element is mounted on or in a wall or ceiling.

43. The optical communications system of claim 39, further comprising an optical filter coupled to a receiver;

44. The optical communication system of claim 43, wherein the emitter is polarized and the optical filter is polarized.

45. The optical communication system of claim 39, further comprising a window filter blocking transmission of wavelengths associated with the emitter.

46. A free space optical communications receiver system for a mobile device, comprising a receiver for receiving a spread laser beam carrying data from a transmitter that received a laser beam from an emitter cluster and created the spread laser beam that was spread over an area sufficient to reduce a power density of the laser beam to an eye safe level.

47. The receiver system of claim 46, wherein the spread laser beam delivers a wide beam of data to the receiver.

48. The receiver system of claim 46, further comprising an optical filter coupled to the receiver.

49. The receiver system of claim 48, wherein the emitter cluster is polarized and the optical filter is polarized.

50. An optical switching device comprising:

- a first cluster of laser emitters emitting a first laser beam;
- a second cluster of laser emitters emitting a second laser beam;
- a first optical element coupled to a first channel;
- a second optical element coupled to a second channel;
- a lens configured to receive the first laser beam and output a beam directed to the first optical element;
- a lens configured to receive the second laser beam and output a beam directed to the second optical element; and
- circuitry configured to drive the first cluster of laser emitters based on data to be transmitted to the first channel, and to drive the second cluster of laser emitters based on data to be transmitted to the second channel.

51. The optical switching device of claim 50, wherein a single lens includes the lens configured to receive the first laser beam and the lens configured to receive the second laser beam.

52. The optical switching device of claim 50, further comprising one or more additional optical elements.

53. The optical switching device of claim 50, wherein the one or more additional optical elements include at least one of a diffuser, a mirror, and a MEMS device.

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