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(54) **DIRECT AND INDIRECT LIGHT DIFFUSING DEVICES AND METHODS**

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***G02B 17/00*** (2006.01)
***G02B 27/30*** (2006.01)
***G02B 5/02*** (2006.01)

(52) **U.S. Cl.** ........ **359/591**; 359/593; 359/597; 359/598; 359/599; 52/22; 52/198; 52/200; 52/244; 52/245

(58) **Field of Classification Search** .......... 359/591–599, 359/641; 52/17, 22, 28–29, 173.3, 199–200, 52/244–245; 126/623; 385/900
See application file for complete search history.

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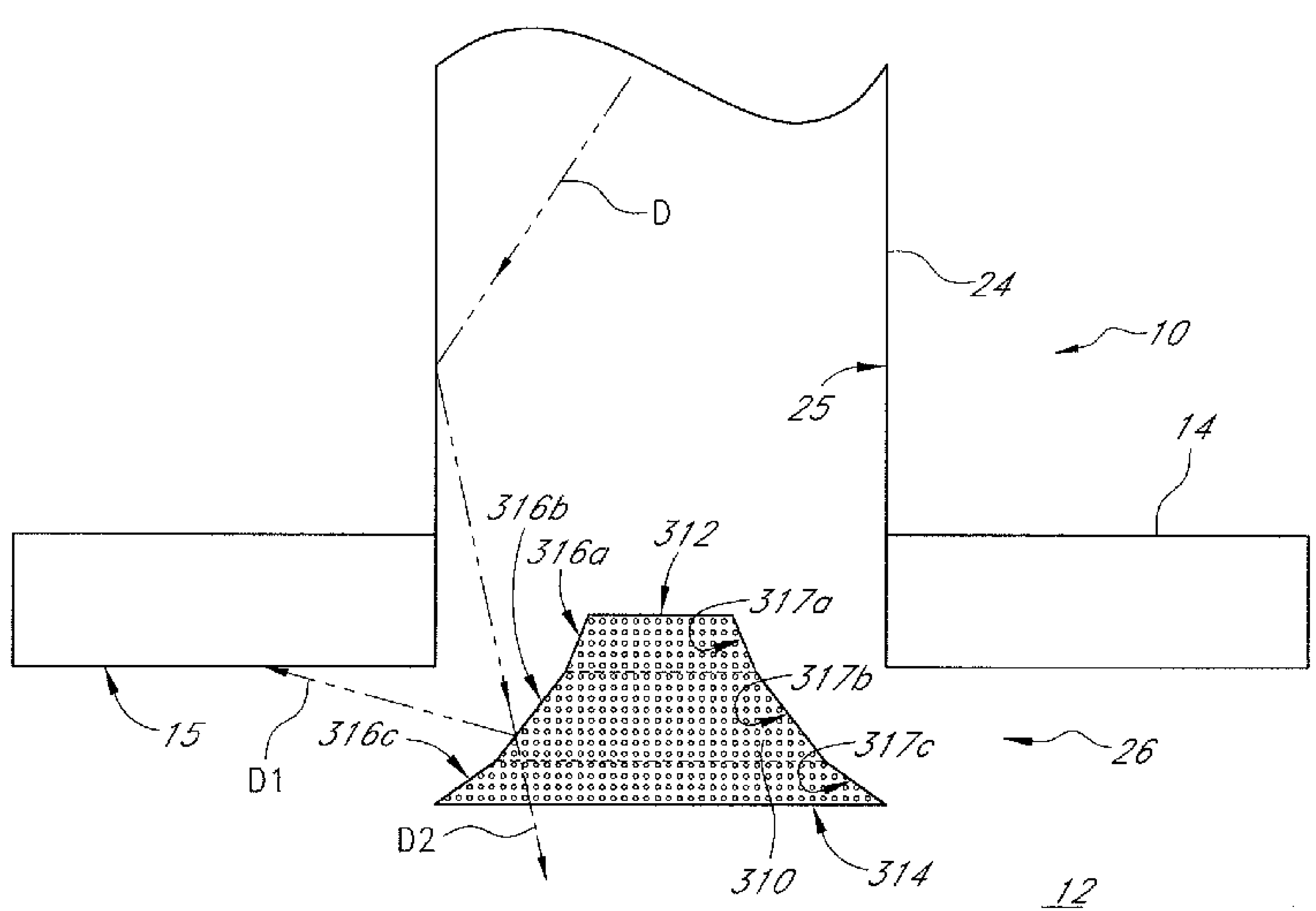
(57) **ABSTRACT**

Some embodiments provide a daylighting apparatus comprising an internally reflective tube configured to direct daylight from a first end of the tube to a second end of the tube opposite the first end. A diffuser can be positioned at the second end of the tube. The diffuser can comprise a first optical structure configured such that, when the daylighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room, a reflected portion of the daylight is directed towards at least one upper region (e.g., a ceiling or upper wall surface) of the room and a transmitted portion of the daylight is directed towards at least one lower region (e.g., a floor surface) of the room.

**12 Claims, 10 Drawing Sheets**



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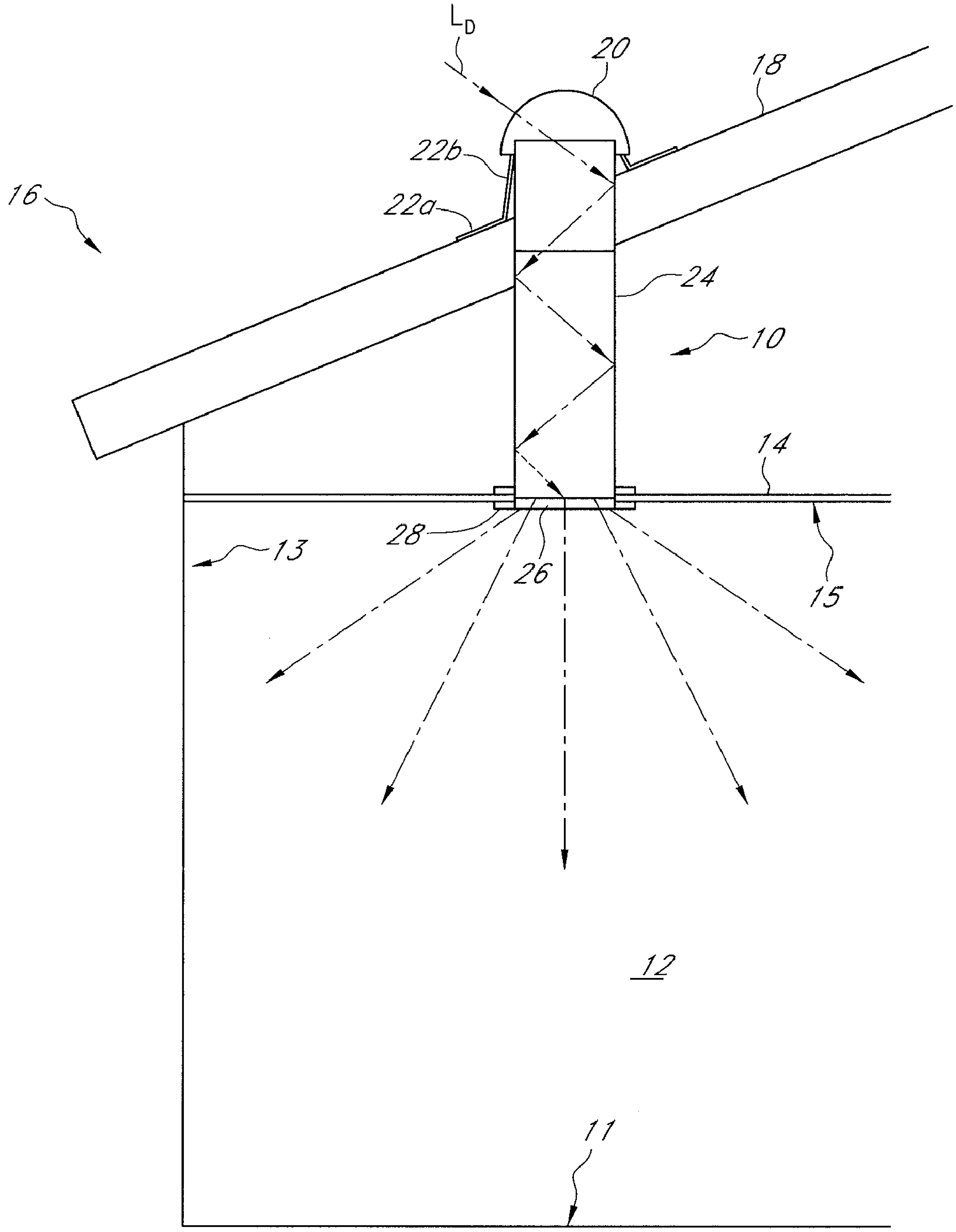


FIG. 1

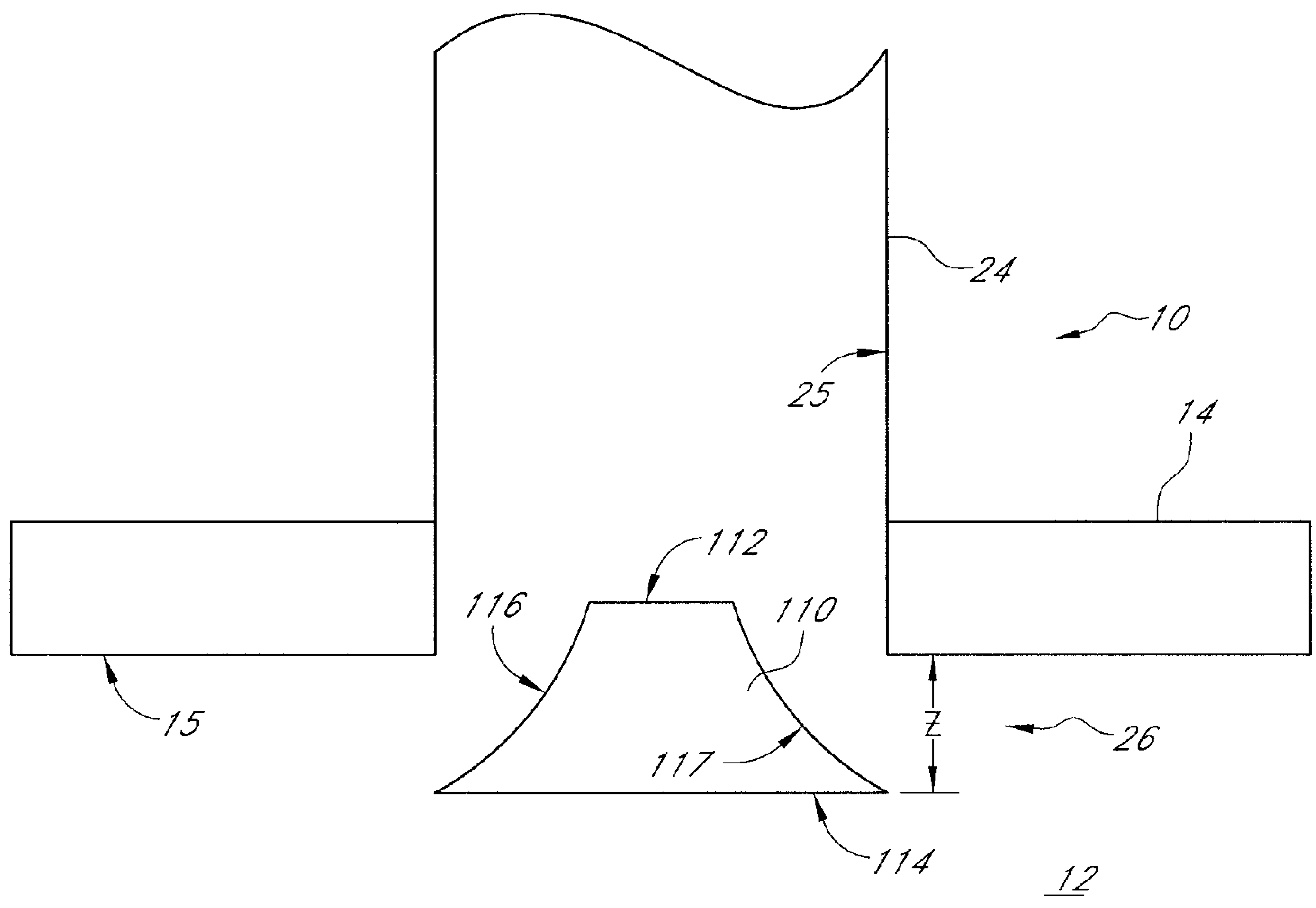


FIG. 2A

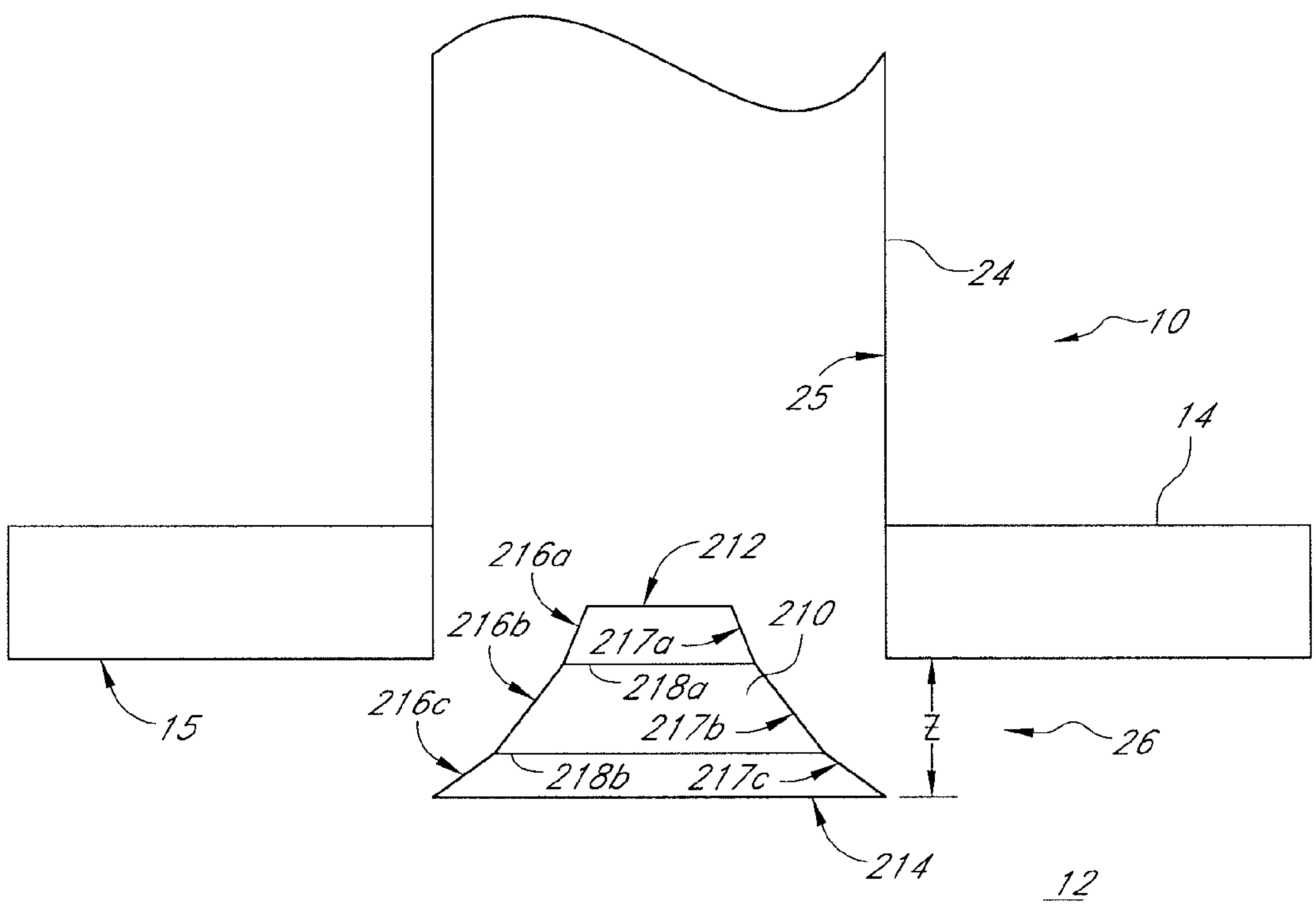
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FIG. 2B

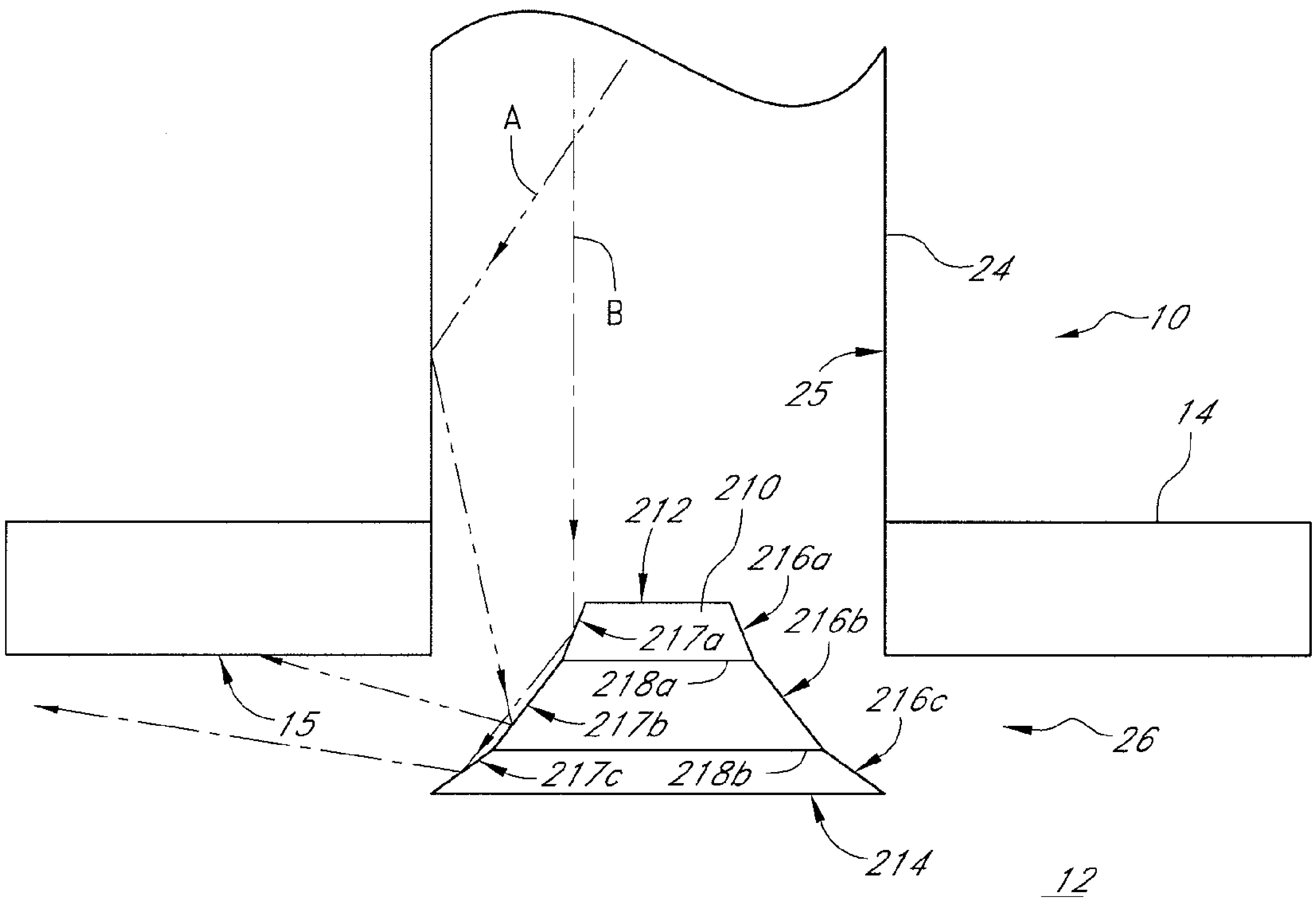
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FIG. 3

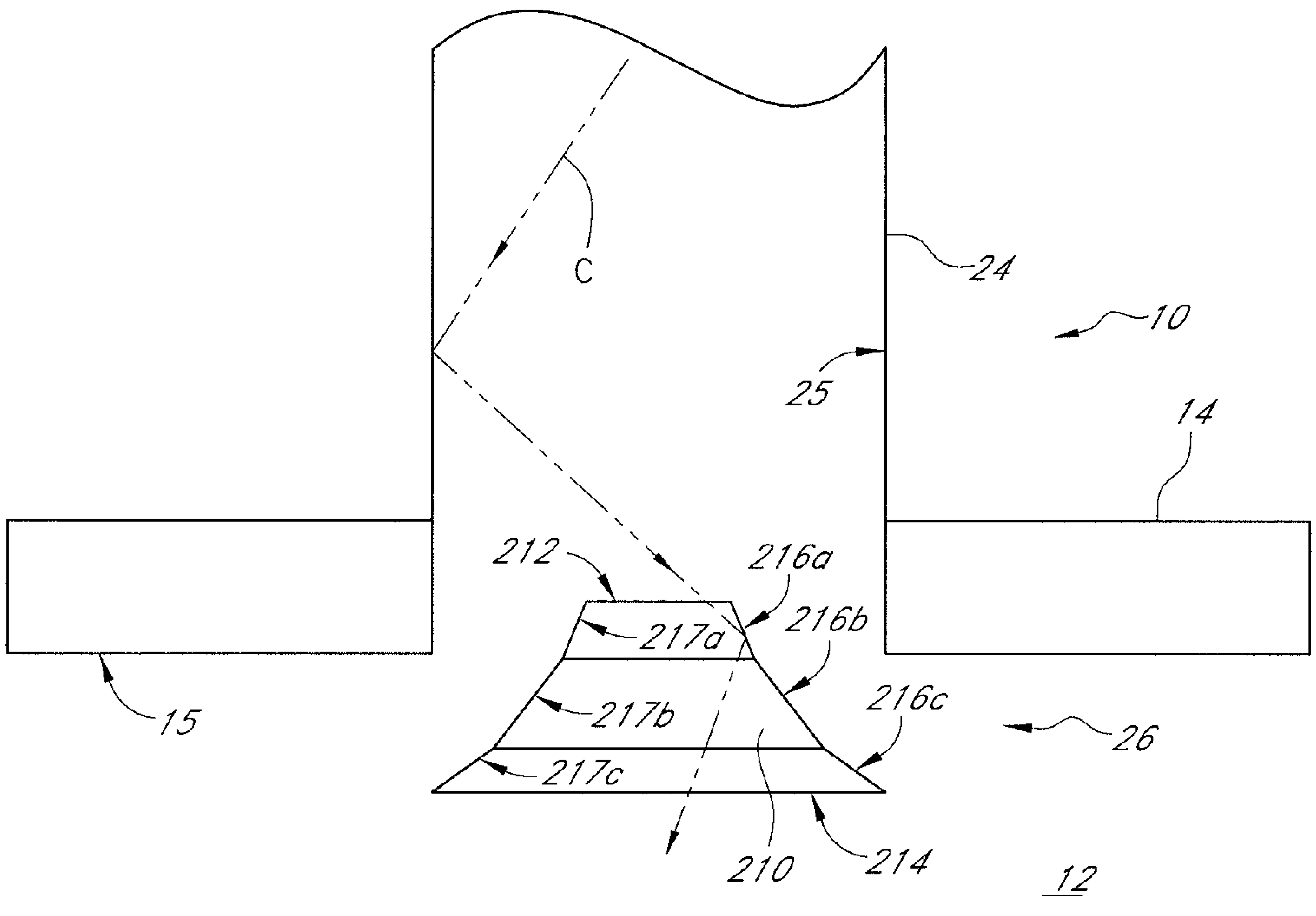


FIG. 4

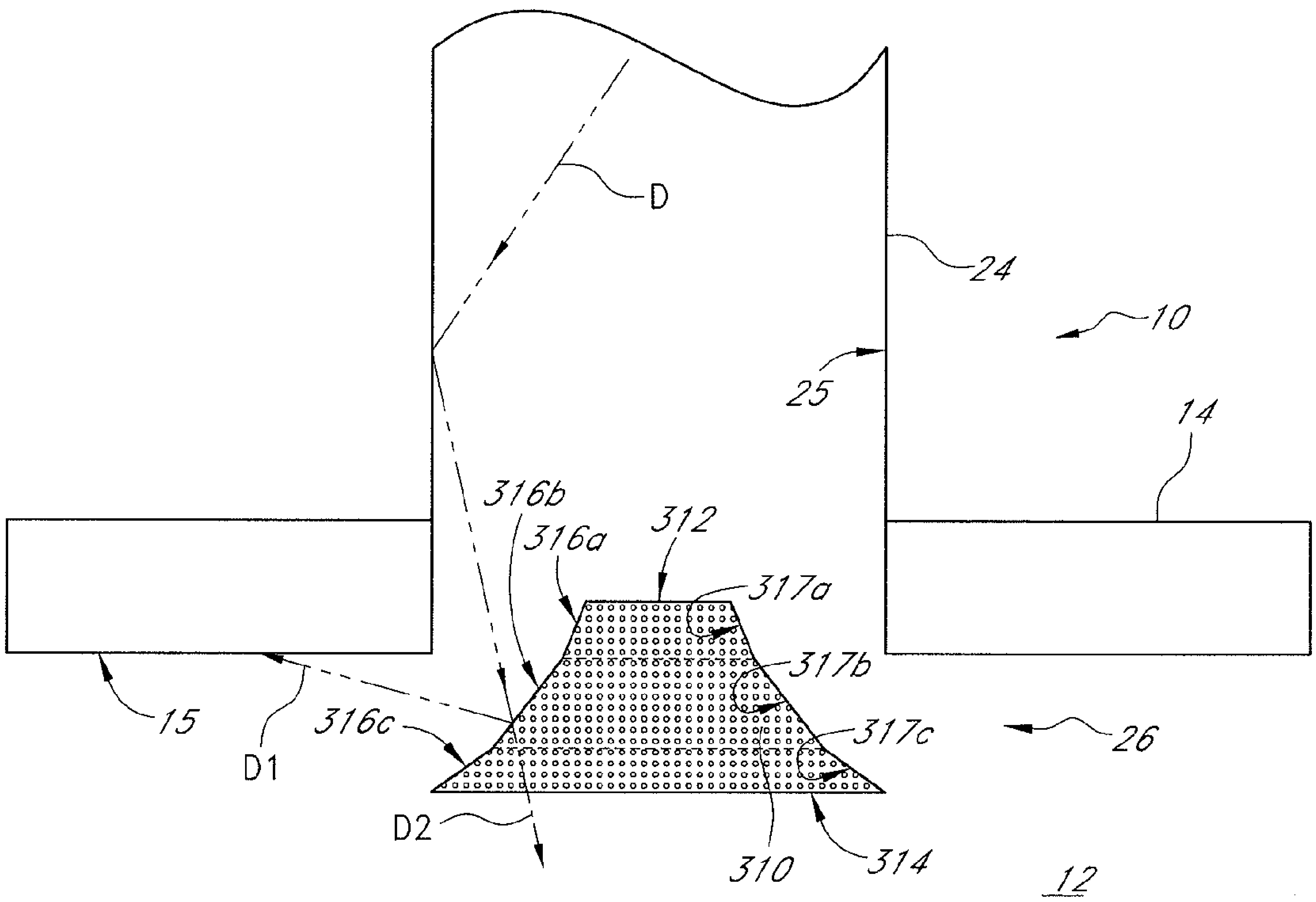
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FIG. 5

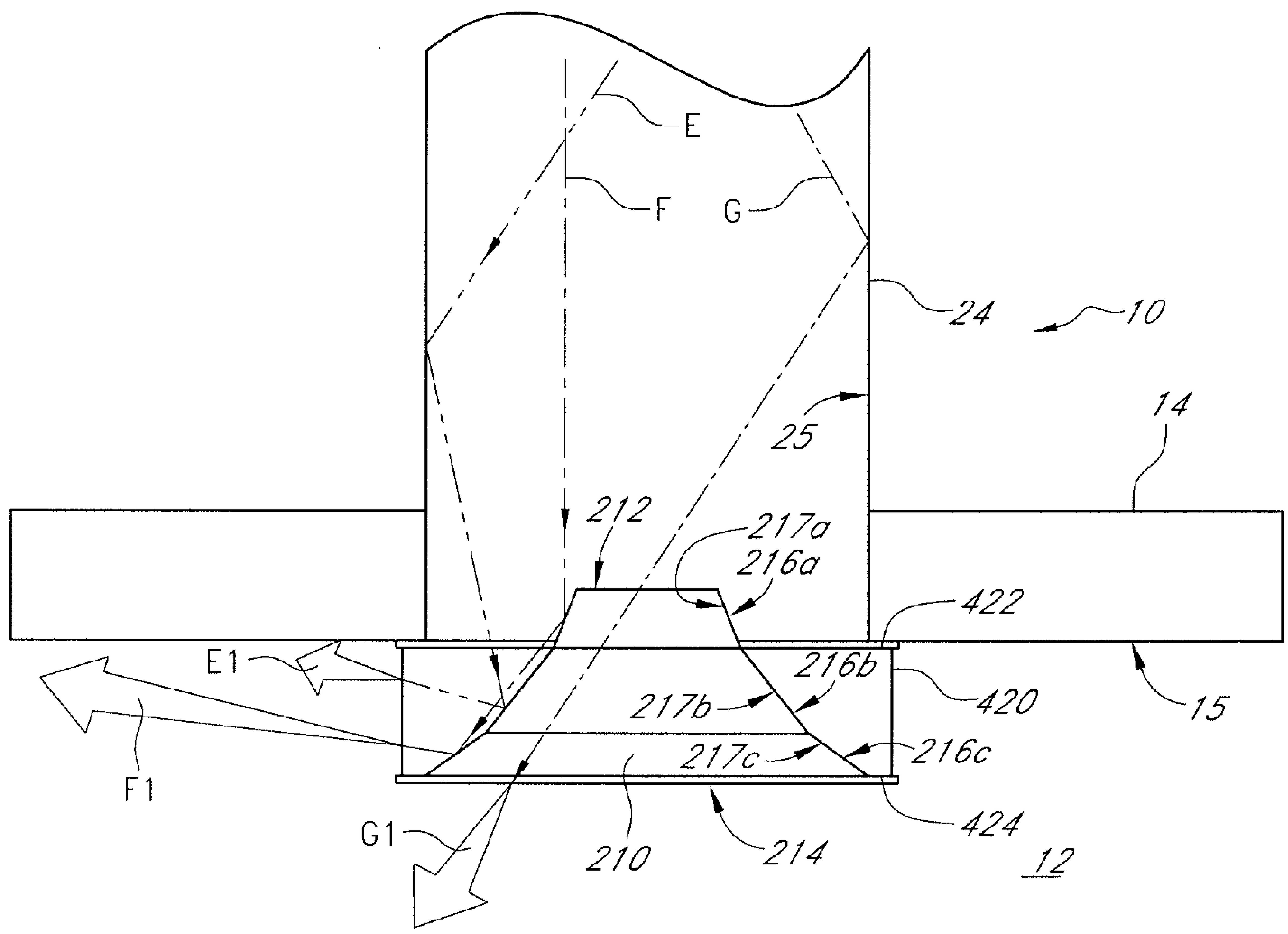
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FIG. 6

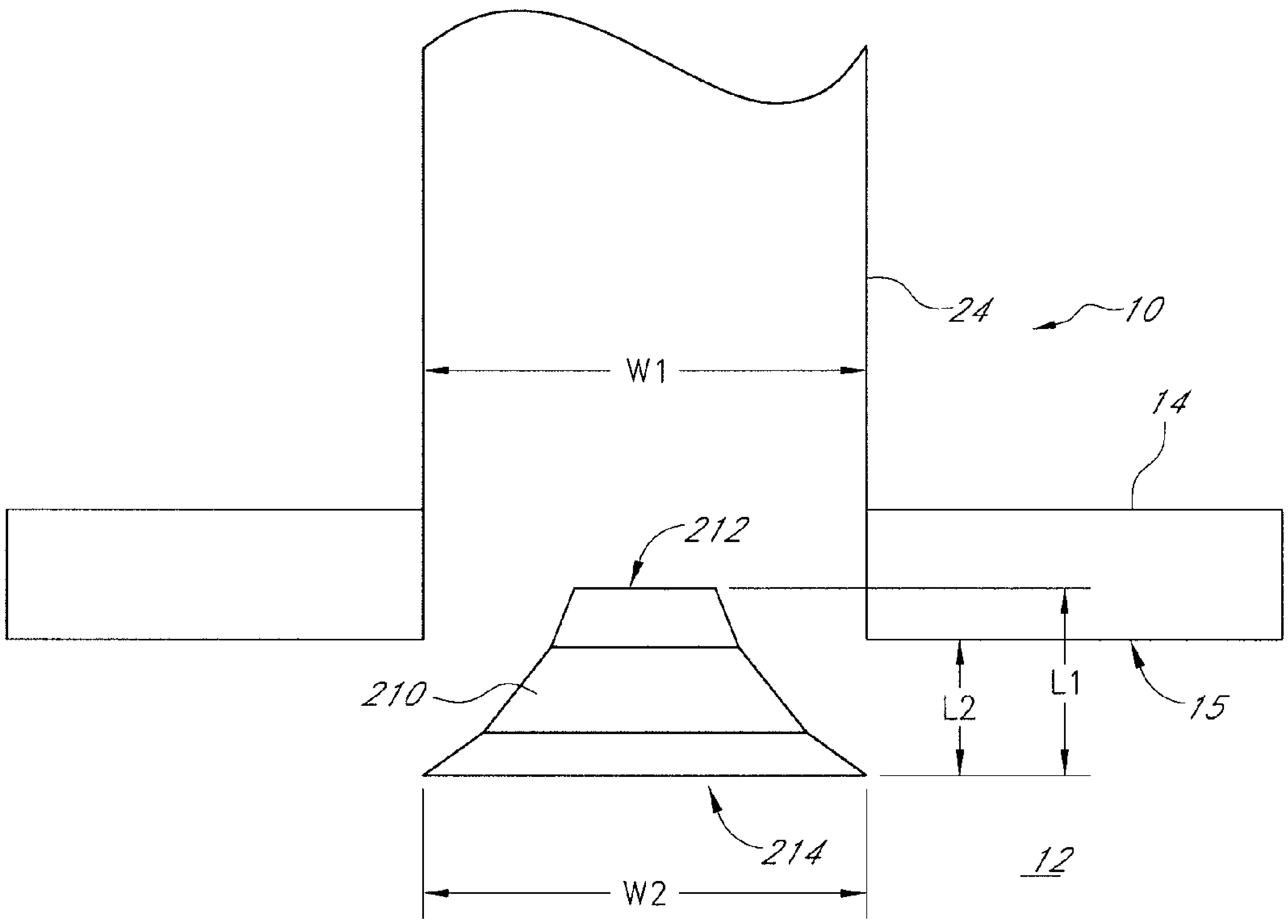


FIG. 7

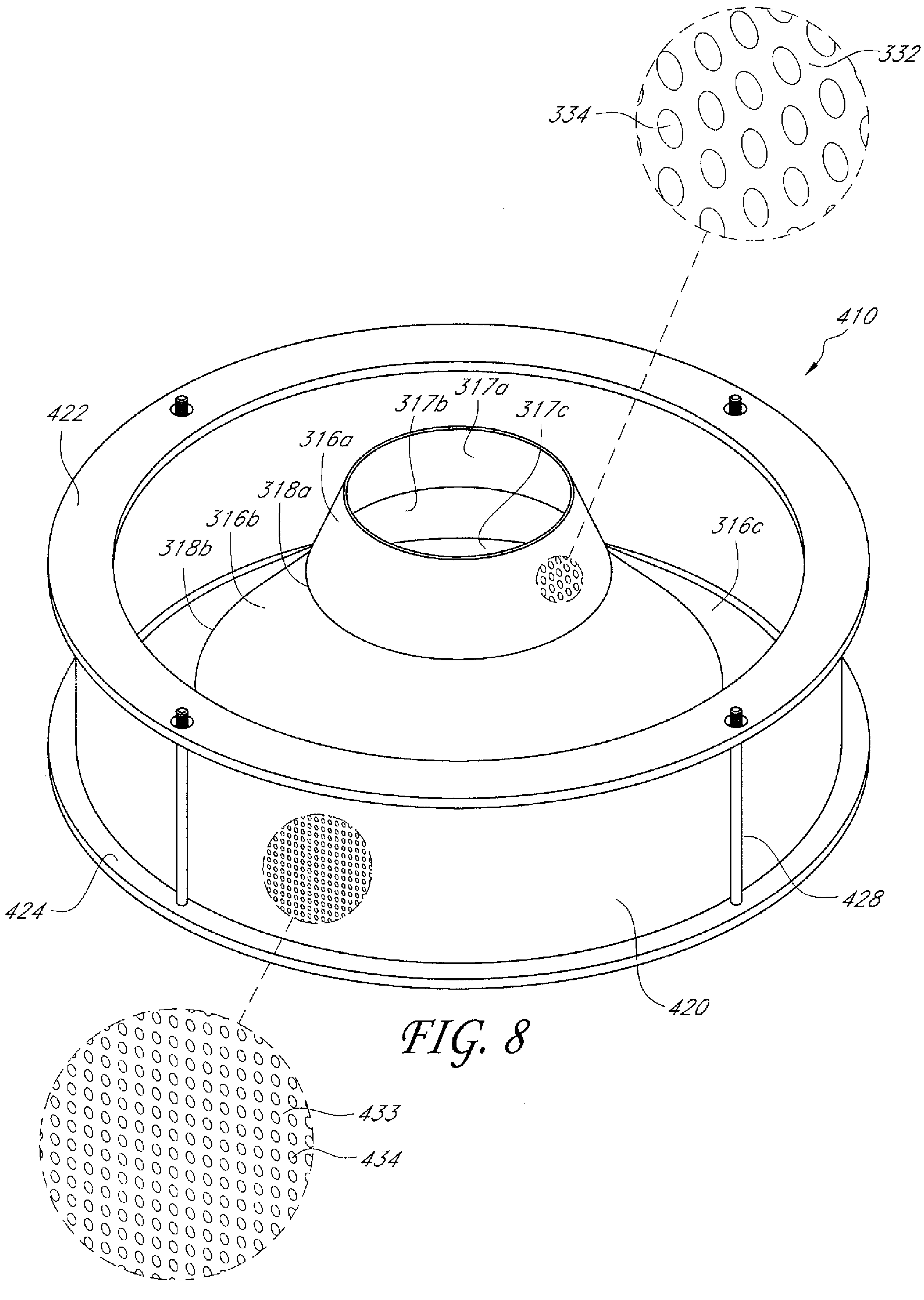
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FIG. 8

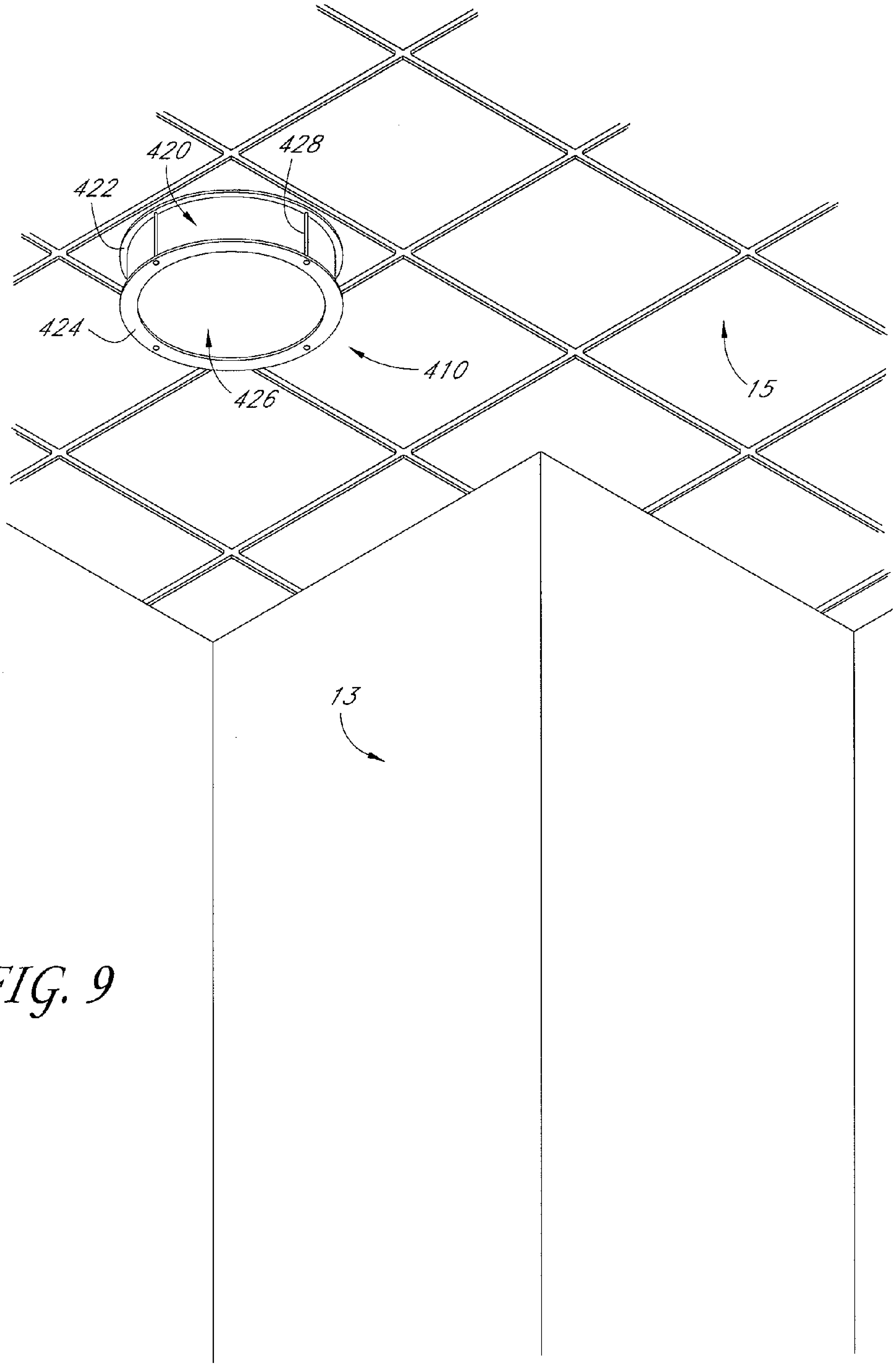


FIG. 9

# DIRECT AND INDIRECT LIGHT DIFFUSING DEVICES AND METHODS

## BACKGROUND

1. Field

This disclosure relates generally to daylighting systems and methods and more particularly to light diffusing devices and methods.

2. Description of Related Art

Daylighting systems typically include windows, openings, and/or surfaces that provide natural light to the interior of a structure. Examples of daylighting systems include skylight and tubular daylighting device (TDD) installations. In a TDD installation, a transparent cover can be mounted on a roof of a building or in another suitable location. An internally reflective tube can connect the cover to a diffuser mounted in a room or area to be illuminated. The diffuser can be installed in a ceiling of the room or in another suitable location. Natural light entering the cover on the roof can propagate through the tube and reach the diffuser, which disperses the natural light throughout the interior of the structure. Certain currently known devices and methods for diffusing light suffer from various drawbacks.

## SUMMARY

Example embodiments described herein have several features, no single one of which is indispensable or solely responsible for their desirable attributes. Without limiting the scope of the claims, some of the advantageous features will now be summarized.

Some embodiments provide a daylighting apparatus comprising an internally reflective tube configured to direct daylight from a first end of the tube to a second end of the tube opposite the first end. A diffuser can be positioned at the second end of the tube. The diffuser can comprise a first optical structure configured such that, when the daylighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room, a reflected portion of the daylight is directed towards at least one upper region (e.g., a ceiling or upper wall surface) of the room and a transmitted portion of the daylight is directed towards at least one lower region (e.g., a floor surface) of the room.

The first optical structure can comprise a reflective surface shaped and positioned to change the direction of propagation of the reflected portion of the daylight. The reflective surface can comprise at least a first face configured to reflect collimated daylight at a first incident angle. The reflective surface can comprise at least a second face configured to reflect the collimated daylight at a second incident angle different from the first incident angle. The reflective surface can comprise a plurality of additional faces.

The reflective surface can comprise at least a first curved face configured to reflect collimated daylight at a plurality of incident angles. The reflective surface can comprise a lower reflective face region, a middle reflective face region, and an upper reflective face region. Each of the lower reflective face region, the middle reflective face region, and the upper reflective face region can be a conical frustum. The first optical structure can comprise a reflective element with many different shapes, such as the general shape of a frustum of a hyperboloid.

The first optical structure can comprise at least one aperture shaped and positioned to permit at least some of the transmitted portion of the daylight to pass through the first optical structure. The first optical structure can comprise at least one reflective surface interrupted by a plurality of openings configured to permit at least some of the transmitted portion of the daylight to pass through the first optical structure.

The diffuser can comprise a second optical structure configured to receive light exiting the first optical structure. The second optical structure can be configured to spread the reflected portion of the daylight. The second optical structure can also be configured to spread the transmitted portion of the daylight.

Certain embodiments provide a method of providing light inside of a structure. The method can comprise the steps of positioning an internally reflective tube between a first location outside the structure and a second location in a room of the structure in a manner that permits daylight to be directed along the tube from the first location to the second location and positioning a diffuser at an end of the tube in the room such that the diffuser reflects a first substantial portion of the daylight exiting the tube towards at least one upper region (e.g., a ceiling and wall surface) of the room and permits a second substantial portion of the daylight exiting the tube to pass through the diffuser towards at least one lower region (e.g., a floor surface) of the room.

Positioning a diffuser can comprise positioning a first optical element configured to reflect at least some of the daylight and positioning a second optical element around the first optical element. The second optical element can be configured to spread the daylight exiting the tube. Positioning a diffuser at an end of the tube can comprise positioning an optical element such that it extends at least partially into the tube.

Some embodiments provide a method of manufacturing a daylighting device. The method can comprise the steps of disposing a reflective material on each side of a substrate to form at least one sheet having two reflective surfaces; cutting or otherwise forming the sheet to include a plurality of openings in the sheet; shaping the at least one sheet to form an optical element having at least one reflective face region with a generally circular cross-section and an aperture extending through the at least one reflective face region; and placing the optical element at one end of an internally reflective tube. The tube can be configured to receive daylight and to direct the daylight towards the optical element. Shaping the at least one sheet can comprise shaping at least a first sheet and a second sheet and joining the first sheet and the second sheet to form the optical element.

The method can comprise the step of placing a second optical element over the first optical element, the second optical element configured to spread light exiting the tube. The optical element can be configured such that, when the daylighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room, a reflected portion of the daylight is directed towards at least one ceiling or wall surface of the room and a transmitted portion of the daylight is directed towards at least one floor surface of the room.



## BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments are depicted in the accompanying drawings for illustrative purposes, and should in no way be interpreted as limiting the scope of the inventions. In addition, various features of different disclosed embodiments can be combined to form additional embodiments, which are part of this disclosure. Any feature or structure can be removed or omitted. Throughout the drawings, reference numbers may be reused to indicate correspondence between reference elements.

FIG. **1** schematically illustrates an example of a TDD installation.

FIG. **2**A is a cross-sectional detail view of an example TDD installation with an optical element having a generally continuously-curved reflective surface.

FIG. **2**B is a cross-sectional detail view of an example TDD installation with an optical element having a reflective surface with multiple faces in a segmented shape.

FIG. **3** is a ray diagram illustrating a propagation of light through the example TDD installation illustrated in FIG. **2**B.

FIG. **4** is another ray diagram illustrating a propagation of light through the example TDD installation illustrated in FIG. **2**B.

FIG. **5** is a ray diagram illustrating a propagation of light through an example TDD installation with a perforated optical element.

FIG. **6** is a ray diagram illustrating a propagation of light through an example TDD installation with a first optical element and a second optical element.

FIG. **7** is a cross-sectional view showing certain dimensions and proportions of an example TDD installation with a diffuser.

FIG. **8** is a perspective view of an example diffuser and an example additional optical element.

FIG. **9** is a perspective view of an example TDD installation with a diffuser and an additional optical element.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Although certain preferred embodiments and examples are disclosed below, inventive subject matter extends beyond the specifically disclosed embodiments to other alternative embodiments and/or uses, and to modifications and equivalents thereof. Thus, the scope of the claims appended hereto is not limited by any of the particular embodiments described below. For example, in any method or process disclosed herein, the acts or operations of the method or process may be performed in any suitable sequence and are not necessarily limited to any particular disclosed sequence. Various operations may be described as multiple discrete operations in turn, in a manner that may be helpful in understanding certain embodiments; however, the order of description should not be construed to imply that these operations are order dependent. Additionally, the structures, systems, and/or devices described herein may be embodied as integrated components or as separate components. For purposes of comparing various embodiments, certain aspects and advantages of these embodiments are described. Not necessarily all such aspects or advantages are achieved by any particular embodiment. Thus, for example, various embodiments may be carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other aspects or advantages as may also be taught or suggested herein.

In some embodiments, a TDD installation transports sunlight from the roof of a building to the interior via a tube with a reflective surface on the tube interior. A TDD installation can sometimes also be referred to as a "tubular skylight." A TDD installation can include a transparent cover installed on the roof of a building or in another suitable location. A tube with a reflective surface on the tube interior extends between the cover and a diffuser installed at the base of the tube. The transparent cover can be dome-shaped or can have another suitable shape and can be configured to capture sunlight. In certain embodiments, the cover keeps environmental moisture and other material from entering the tube. The diffuser spreads light from the tube into the room or area in which the diffuser is situated.

The cover can allow exterior light, such as daylight, to enter the system. In some embodiments, the cover includes a light collection system configured to enhance or increase the daylight entering the tube. In certain embodiments, a TDD installation includes a light mixing system. For example, the light mixing system can be positioned in the tube or integrated with the tube and can be configured to transfer light in the direction of the diffuser. The diffuser can be configured to distribute or disperse the light generally throughout a room or area inside the building. Various diffuser designs are possible. An auxiliary lighting system can be installed in a TDD to provide light from the tube to the targeted area when daylight is not available in sufficient quantity to provide a desired level of interior lighting.

The direction of light reflecting through the tube can be affected by various light propagation factors. Light propagation factors include the angle at which the light enters the TDD, which can sometimes be called the "entrance angle." The entrance angle can be affected by, among other things, the solar elevation, optics in the transparent cover, and the angle of the cover with respect to the ground. Other light propagation factors include the slope of one or more portions of a tube sidewall and the specularity of the sidewall's internal reflective surface. The large number of possible combinations of light propagation factors throughout a single day can result in light exiting the TDD at a wide and continuously varying range of angles.

FIG. **1** shows a cutaway view of an example of a TDD **10** installed in a building **16** for illuminating, with natural light, an interior room **12** of the building **16**. The TDD **10** includes a transparent cover **20** mounted on a roof **18** of the building **16** that allows natural light to enter a tube **24**. The cover **20** can be mounted to the roof **18** using a flashing. The flashing can include a flange **22***a* that is attached to the roof **18**, and a curb **22***b* that rises upwardly from the flange **22***a* and is angled as appropriate for the cant of the roof **18** to engage and hold the cover **20** in a generally vertically upright orientation. Other orientations are also possible.

The tube **24** can be connected to the flashing **22** and can extend from the roof **18** through a ceiling **14** of the interior room **12**. The tube **24** can direct light $L_D$ that enters the tube **24** downwardly to a light diffuser **26**, which disperses the light in the room **12**. The interior surface **25** of the tube **24** can be reflective. In some embodiments, the tube **24** has at least a section with substantially parallel sidewalls (e.g., a generally cylindrical surface). Many other tube shapes and configurations are possible. The tube **24** can be made of metal, fiber, plastic, a rigid material, an alloy, another appropriate material, or a combination of materials. For example, the body the tube **24** can be constructed from type 1150 alloy aluminum. The shape, position, configuration, and materials of the tube **24** can be selected to increase or maximize the portion of daylight $L_D$ or other types of light entering the tube **24** that propagates into the room **12**.

The tube **24** can terminate at or be functionally coupled to a light diffuser **26**. The light diffuser **26** can include one or more devices that spread out or scatter light in a suitable manner across a larger area than would result without the diffuser **26** or devices thereof. In some embodiments, the diffuser **26** permits most or substantially all visible light traveling down the tube **24** to propagate into the room **12**. The diffuser can include one or more lenses, ground glass, holographic diffusers, other diffusive materials, or a combination of materials. The diffuser **26** can be connected to the tube **24** using any suitable connection technique. For example, a seal ring **28** can be surroundingly engaged with the tube **24** and connected to the light diffuser **26** in order to hold the diffuser **26** onto the end of the tube **24**. In some embodiments, the diffuser **26** is located in the same general plane as the ceiling **14**, generally parallel to the plane of the ceiling, or near the plane of the ceiling **14**.

In certain embodiments, the diameter of the diffuser **26** is substantially equal to the diameter of the tube **24**, slightly greater than the diameter of the tube **24**, slightly less than the diameter of the tube **24**, or substantially greater than the diameter of the tube **24**. The diffuser **26** can distribute light incident on the diffuser toward a lower surface (e.g., the floor **11**) below the diffuser and, in some room configurations, toward an upper surface (e.g., at least one wall **13** or ceiling surface **15**) of the room **12**. The diffuser **26** can spread the light such that, for example, light from a diffuser area of at least about 1 square foot and/or less than or equal to about 4 square feet can be distributed over a floor and/or wall area of at least about 60 square feet and/or less than or equal to about 200 square feet in a typical room configuration.

Diffusers that employ principally direct diffusion, such as downward directing diffusers, distribute light in certain ways that can be undesirable. Some direct diffusers distribute light such that the intensity of light on the floor **11** when measured on a horizontal plane is highest directly under the diffuser **26** and decreases with distance away from the location directly under the diffuser **26**. In some instances, the distribution of light on the floor is characterized by a cosine effect. For example, the intensity of the light can be directly related to the cosine of the incident angle of the light to the floor and inversely related to the distance between the diffuser **26** and the floor. Accordingly, non-uniform floor light levels are typically observed when certain types of diffusers are used in a TDD **10**. Further, certain types of direct diffusers are characterized by intense light exiting the diffuser **26** from ceiling levels less than 15 feet at angles of 45 to 60 degrees (measured from vertical). Intense light at those angles can create visibility problems in an area, including glare and computer screen washout. The contrast of the bright diffuser area and the dark non-illuminated ceiling can also increase the perceived glare and reduce the view of the ceiling area. These are some common undesirable characteristics related to downward directing diffusers.

Diffusers that employ principally indirect diffusion typically distribute light principally to the ceiling and/or walls of an area. Indirect diffusers can also distribute light in ways that are undesirable. For example, indirect diffusers typically distribute a smaller portion of light to the floor **11** or working areas than direct diffusers. Thus, there may be a substantially dark or dimly-lit area on the floor **11** directly under the TDD **10**.

In some embodiments, a diffuser **26** provides substantial amounts of both direct diffusion and indirect diffusion. In certain embodiments, a diffuser **26** redirects a portion of the light $L_D$ that exits the tube **26** at the ceiling level onto a surrounding supper region (e.g., a ceiling surface **15**) and distributes the remainder to a lower region (e.g., the floor **11** and walls **13**). Such a diffuser **26** can illuminate the floor **11** more uniformly. Light $L_D$ that is projected onto the painted ceiling surface **15** and walls **13** will reflect off of these surfaces **13**, **15** in a diffuse, widespread pattern that will mix the light considerably before reaching the floor level **11**. Allowing a portion or fraction of the light $L_D$ to pass directly to the floor **11** through a diffuser **26** or light spreading device can mitigate or eliminate the occurrence of a dark area under the TDD **10**.

In some embodiments, a diffuser **26** reduces the light intensity in a region greater than or equal to about 45° and/or less than or equal to about 60° azimuthally away from the axis of the tube **24** by distributing more light $L_D$ upward to the ceiling surface **15**, thereby eliminating or reducing the incidence of glare and display washout. Further, light that passes through the hollow interior of the diffuser **26** can be directed or controlled such that it has an exit angle of less than about 45° from vertical. When at least the areas of the ceiling surface **15** near the TDD **10** or other areas generally in the upper portion of the room **12** are illuminated, the contrast ratio between the diffuser **26** and the surrounding ceiling surface **15** can be reduced, and a brighter overall room appearance can be created.

In the embodiments illustrated in FIGS. **2A-2B**, an optical element **110** is suspended below the level of the ceiling **14** in order to direct light onto the ceiling surface **15**. The distance z that the optical element **110** extends below the ceiling **14** can be selected such that the optical element **110** directs adequate light towards the ceiling surface **15** while not substantially intruding into the available space of the room **12**. Factors that may affect the selection of the distance z can include ceiling height, other room dimensions, aesthetics, other functional or architectural factors, or a combination of factors. For example, a shorter distance z may be selected when the TDD **10** is installed in a room **12** with low ceiling height. In some embodiments, the distance z is less than the height of the diffuser **26**.

As shown in FIG. **2A**, the diffuser **26** can include a curved optical element **110** placed directly below and partially inside the base of the tube **24**. In the example embodiment illustrated in FIG. **2A**, the shape of the optical element **110** can generally conform to a right circular, outwardly concave frusto-hyperbolic section. Many other variations in the shape of the optical element **110** are possible. In some embodiments, the optical element **110** is shaped to reflect light incident over the area of the element **110** at a plurality of incident angles such that light turned by the optical element **110** is dispersed over a relatively large angular range (for example, at least about 180° or at least about 200°). In certain embodiments, the light incident on the optical element **110** is substantially collimated while the light exiting the optical element **110** is substantially distributed throughout the room **12** in which the TDD **10** is installed. In some embodiments, the distribution of light exiting the optical element **110** includes a substantial portion of light dispersed across each of the upper and lower regions (e.g., the ceiling surface **15**, walls **13**, and floor **11**) of the room **12**.

The optical element **110** can be constructed from a material system including, for example, metal, plastic, paper, glass, ceramic, a coating, a film, another suitable material, or a combination of materials. In some embodiments, the optical element **110** includes an aluminum substrate with a reflective coating on each face. The optical element **110** illustrated in FIG. **2A** has a reflective, concave outer face **116** that extends circumferentially about an axis. The outer face **116** faces away from the axis, while a reflective, convex inner face **117** opposite the outer face **116** faces towards the axis, toward the hollow interior of the optical element **110**. In certain embodiments, the central axis of the optical element **110** is substantially collinear with a central axis of the tube **24**.

The surfaces of the outer face **116** and the inner face **117** can be made reflective by any suitable technique, including, for example, electroplating, anodizing, coating, or covering the surfaces **116**, **117** with a reflective film. Reflective films can be highly reflective in at least the visible spectrum and include metallic films, metalized plastic films, multi-layer reflective films, or any other structure that substantially reflects light in the visible spectrum. The material from which the optical element **110** is constructed may also be inherently reflective. In some embodiments, at least a portion of the surfaces of the outer face **116** and the inner face **117** are generally specular.

A top plane **112** of the optical element **110** is generally open so that light traveling down the tube **24** can pass into the hollow interior of the element **110**. A bottom plane **114** of the element **110** is also generally open such that light propagating through the interior of the element **110** can exit the element **110** and enter the room **12** below in the general direction of the floor **11**. The aperture of the top plane **112** and the aperture of the bottom plane **114** can be substantially circular or any other suitable shape. In some embodiments, one or more of the apertures are the same shape as the shape of a cross-section of the tube **24**. In certain embodiments, the diameter of the bottom plane **114** aperture is substantially equal to the diameter of the tube **24**, slightly greater than the diameter of the tube **24**, slightly less than the diameter of the tube **24**, or substantially greater than the diameter of the tube **24**. The diameter of the top plane **112** aperture can be smaller than the diameter of the bottom plane **114** aperture, less than or equal to about half the diameter of the bottom plane **114** aperture, less than or equal to about 75% of the diameter of the bottom plane **114** aperture, or another suitable diameter. In some embodiments, the diameter of the top plane **112** aperture is selected to achieve a desired ratio of direct diffusion to indirect diffusion. For example, if a higher ratio of direct diffusion to indirect diffusion is desired, then the diameter of the aperture of the top plane **112** can be increased.

In some embodiments, the typical incident angle of substantially collimated light propagating down the tube **24** and incident on the optical element **110** depends on whether the light is incident on one of the reflective faces **116**, **117** at a position near the top plane **112** or whether the light is incident at a position near the bottom plane **114** of the optical element **110**. In the example illustrated embodiment, the shape of the faces **116**, **117** permits the angle of incidence for collimated incoming light to be larger at positions closer to the top plane **112** and comparatively smaller at positions closer to the bottom plane **112** of the optical element **110**. While FIG. **2**A shows an optical element **110** with reflective faces **116**, **117** having a particular curvature, it is understood that faces **116**, **117** having other curvature or shapes can be used. For example, in some embodiments, the vertical cross-section of the faces **116**, **117** (for example, the cross-section shown in FIG. **2**A) can have a generally elliptical shape, a generally hyperbolic shape, a generally parabolic shape, a generally negative intrinsic curvature, a generally positive intrinsic curvature, another geometry, or a combination of differently-shaped regions. The shape of the faces **116**, **117** can be selected such that a substantial amount of light is directed towards the floor **11**, wall **13**, and ceiling surfaces **15** of the room **12** when the optical element **110** is positioned below the tube **24** in a TDD **10** installation.

The example diffuser **26** illustrated in FIG. **2**B includes an optical element **210** having a shape generally conforming to a plurality (e.g., three) contiguous right circular frustoconical sections. Many other variations in the shape of the optical element **210** are possible. The illustrated optical element **210** has a hollow interior and can be placed below and partially inside the tube **24**. In some embodiments, the optical element **210** has a plurality of faces **216***a-c*, **217***a-c* oriented at various angles to reflect light incident over the area of the element **210** at a plurality of incident angles such that light turned by the optical element **210** is dispersed over a relatively large angular range (for example, at least about 180° or at least about 200°). In certain embodiments, the light incident on the optical element **210** is substantially collimated while the light exiting the optical element **210** is substantially distributed throughout the room **12** in which the TDD **10** is installed. In some embodiments, the distribution of light exiting the optical element **210** includes a substantial portion of light dispersed across each of the upper and lower regions (e.g., the ceiling surface **15**, walls **13**, and floor **11**) of the room **12**.

The optical element **210** can be constructed from a variety of materials, including the materials discussed with respect to the optical element **110** described previously. The optical element **210** illustrated in FIG. **2**B has a plurality of reflective outer faces **216***a-c* that extend generally circumferentially about an axis. The outer faces **216***a-c* face away from the axis, while a plurality of reflective inner faces **217***a-c* generally opposite the outer faces **216***a-c* face toward the hollow interior of the optical element **210**. In certain embodiments, the central axis of the optical element **210** is substantially collinear with a central axis of the tube **24**.

A top plane **212** of the optical element **210** is generally open so that light traveling down the tube **24** can pass into the hollow interior of the element **210**. A bottom plane **214** of the element **210** is also open such that light propagating through the interior of the element **210** can exit the element **210** and enter the room **12** below in the general direction of the floor **11**. The shapes and sizes of the top plane **212** aperture and the bottom plane **214** aperture can be selected in at least the same ways as the shapes and sizes of the apertures of the optical element **110** described previously.

In some embodiments, the incident angle of substantially collimated light propagating down the tube **24** and incident on the optical element **210** is different when the light is incident on a surface near the top plane **212** than when the light is incident on a surface near the bottom plane **214** of the optical element **210**. In the example illustrated embodiment, the arrangement of the plurality of faces **216***a-c*, **217***a-c* permits the angle of incidence for collimated incoming light to be larger at the faces **216***a*, **217***a* closer to the top plane **212** ("top faces") of the optical element **210** and comparatively smaller at the faces **216***c*, **217***c* closer to the bottom plane **212** ("bottom faces") of the optical element **210**. The arrangement of the faces **216***b*, **217***b* between the top faces **216***a*, **217***a* and the bottom faces **216***c*, **217***c* ("middle faces") can permit the incident angle of the collimated light at the middle faces **216***b*, **217***b* to be between the incident angle at the top faces **216***a*, **217***a* and the incident angle at the bottom faces **216***c*, **217***c* in magnitude. While the illustrated embodiment has three regions of reflective faces, it is understood that any number of reflective face regions can be employed, including, for example, one region, two regions, four regions, more than four regions, two or more regions, between two and four regions, and so forth.

The number and configuration of exterior faces **116***a-c* and interior faces **117***a-c* can be selected such that a substantial amount of light is directed towards the floor **11**, wall **13**, and ceiling surfaces **15** of the room **12** when the optical element **210** is positioned below the tube **24** in a TDD **10** installation, or such that light is distributed generally uniformly around both upper and lower regions of a room at the same time. For example, in some embodiments light can be distributed by the diffuser **26** generally continuously across a region extending from a plane generally parallel with the base **214** of the optical element **210** to a plane generally perpendicular to the to the diffuser **26** and generally parallel to the axis of the tube **24**. In certain embodiments, light can be distributed by the diffuser **26** generally continuously through an angle sweeping from an upper region of the room **12** generally adjacent to or near the TDD **10** to a lower region of the room **12** generally below the TDD **10**. For example, the diffuser **26** can direct portions of incoming daylight upwards, to the left, to the right, and/or downwards.

The optical element **210** can include transition regions **218***a-b* disposed between reflective faces having differing geometry. For example, a first transition region **218***a* can be disposed between the top faces **216***a*, **217***a* and the middle faces **216***b*, **217***b*, and a second transition region **218***b* can be disposed between the middle faces **216***b*, **217***b* and the bottom faces **216***c*, **217***c*. In some embodiments, the number of transition regions **218***a-b* is equal to one less than the number of reflective face regions having differing geometry. For example, the example embodiment illustrated in FIG. **2**B has three frustoconical face regions having different slant angles and two transition regions **218***a-b*. The transition regions **218***a-b* can include creases, rounded corners, or other transitional elements between reflective face regions. In some embodiments, the transition regions **218***a-b* form a sharp transition between reflective face regions. Alternatively, the transition regions **218***a-b* can form a more gradual transition between reflective face regions.

The optical element **210** can control and distribute light exiting the tube **24** according to various optical element design properties and their associated principles. In the example embodiment illustrated in FIG. **3**, the reflective surfaces **216***a-c*, **217***a-c* of the optical element **210** are designed to accommodate a specific range of angles of light to maintain a constant, a nearly constant, or a substantially evened illumination on the ceiling surfaces **15** and walls (not shown) of the room **12**. Light reflects down the tube **24** at the same elevation angle from horizontal at which the light entered the tube **24**. Therefore, for most inhabited locations on the planet, in many embodiments, the elevation angle from horizontal of light entering the tube **24** will range from about 20 to 70 degrees. The elevation angle depends on the sun angle, which varies throughout the course of a day and also throughout the course of a year.

The propagation of light through the tube **24** and the interaction of light with the optical element **210** vary with the elevation angle of the light. For example, in some embodiments, light A entering at lower sun angles will reflect once off a sloped surface **216***b* of the optical element **210**, as shown in FIG. **3**. In certain such embodiments, light B entering the tube **24** at higher sun angles will reflect multiple times off surfaces **216***a*, **216***c* of the optical element **210**. Accordingly, both the low-angle light A and the high-angle light B are directed towards the ceiling surface **15** at exit angles that are considerably closer than the elevation angles of the light when it entered the tube **24**. By reflecting light differently depending on the elevation angle of the light, the optical element **210** can provide similar exit angles and illumination on the ceiling surface **15** and walls of the room **12** for high elevation angle light and low elevation angle light.

The top plane **212** of the optical element **210** can be open, substantially open, or at least partially open to allow light C to transmit down to the area below the tube **24** (for example, towards the floor of the room **12**). In the example embodiment illustrated in FIG. **4**, light C passes through the top plane **212** and reflects off an interior face **217***a* of the optical element **210**. The interior face **217***a* turns the light C such that the exit angle of the light C from the TDD **10** is closer to vertical than the entrance angle of the light C. In some embodiments, the optical element **210** increases the elevation angle from horizontal of at least a portion of the light propagating through the interior of the optical element **210** such that the at least a portion of the light exits the TDD **10** at a more vertical angle, as illustrated. The degree to which the light C is turned can depend on the orientation and position of the portion of the interior face **217** on which the light C is incident.

In certain embodiments, the optical element **210** is designed to ensure that light passing through the optical element **210** will exit the bottom plane **214** of the optical element **210** at an exit angle of less than about 45 degrees from vertical or at a nearly vertical orientation in order to reduce or prevent the light C from exiting the TDD **10** at a 45 to 60 degree angle from vertical. In this manner, the optical element **210** can reduce or eliminate the glare and visibility issues that light exiting a fixture at those angles can cause.

In the example embodiment illustrated in FIGS. **5** and **8**, an optical element **310** is shown that can resemble the optical elements **110**, **210** described previously in many ways, but differs in manners such as those discussed hereafter. The optical element **310** has exterior faces **316***a-c* and interior faces **317***a-c* that are at least partially reflective and at least partially transmissive. In some embodiments, the optical element **310** is constructed from a material **332** that is perforated, cut, molded, or otherwise constructed such that the material is interrupted by a plurality of openings **334** that extend through the material. The openings **334** can be sized and positioned in order to allow a substantial amount of light D**2** to transmit downward and a substantial amount of light D**1** to be reflected towards the ceiling surfaces **15** or walls of the room **12**. Incident light D is turned when it is incident on the reflective material **332** but transmits through the openings **334**. In some embodiments, the openings **334** are generally evenly distributed over the surface of the optical element **310**. Alternatively, the openings **334** can be distributed according to a pattern that is configured to produce any desired effect.

In some embodiments, the openings **334**, **434** are not true physical openings, but merely optical openings formed of translucent or transparent material surrounded by or adjacent to opaque or reflective material. Other structures or configurations can also be used to permit a portion of the light to be directed generally perpendicularly to the diffuser **26** and a portion of the light to be directed generally in the direction of the periphery of the diffuser **26**.

In certain embodiments, the openings **334** are configured such that the total area encompassed by the openings is about 50% of the surface area of the optical element **310**. Alternatively, the openings can be configured such that the openings **334** cover less than or equal to about 60% of the surface, more than or equal to about 40% of the surface, or another portion that can be selected to give the optical element **310** any desired optical characteristics. By adjusting the size and arrangements of openings **334** in the optical element **310**, a TDD manufacturer can tailor the reflection and transmission characteristics of the optical element **310** to account for the relative amount of illumination needed on the ceiling surface **15**, walls, and/or floor of the room **12**. In certain embodiments, the illumination on the ceiling surface **15**, walls, and/or floor of the room **12** emanating from a TDD installation can be adjusted without increasing or decreasing the size of the tube.

One or more optical elements in addition to the optical elements **210**, **310** described above can be used to further control the distribution of light as it exits the TDD **10**. In the example embodiment illustrated in FIGS. **6**, **8** and **9**, a second optical element **410** is disposed between the optical element **210** and the room **12**. The second optical element **410** is a light diffusing structure configured to interact with light E, F reflected by and/or light G passing through the optical element **210**. In the embodiment illustrated in FIG. **6**, light E propagating along a first path reflects off the interior surface **25** of the tube **24** and is incident on the optical element **210** at a middle exterior face **216***b*. The middle exterior face **216***b* reflects and turns the light E toward the ceiling surface **15**. The light E propagates to the second optical element **410**, which spreads the light. Light E**1** exiting the second optical element **410** is spread in a diffused pattern generally toward the ceiling surfaces **15** and walls **13** of the room **12**. Light F propagating along a second path is incident on the optical element at an upper exterior face **216***a*. The upper exterior face **216***a* reflects and turns the light F toward a lower exterior face **216***c* of the optical element **210**. The lower exterior face **216***c* reflects and turns the light F generally toward the ceiling surface **15**. The light F propagates to the second optical element **410**, which spreads the light. Light F**1** exiting the second optical element **410** is spread in a diffused pattern generally toward the ceiling surfaces **15** and walls **13** of the room **12**. Light G propagating along a third path reflects off the interior surface **25** of the tube **24** and passes through the optical element **210**. The light G propagates to the second optical element **410**, which spreads the light. Light G**1** exiting the second optical element **410** is spread in a diffused pattern generally toward the floor **11** of the room **12**.

Many variations in the shape, position, and construction of the second optical element **410** are possible. The second optical element **410** can include a first diffusing surface **420** extending from the ceiling **14** to the base of the optical element **210**. A second diffusing surface **426** can refract light exiting the base **214** of the optical element **210**. The diffusing surfaces **420**, **426** can be made from any suitable material such as, for example, transparent plastic, translucent plastic, glass, one or more lenses, ground glass, holographic diffusers, another diffusing material, or a combination of materials.

In some embodiments, at least one of the diffusing surfaces **420**, **426** comprises a substantially continuous diffusing material **432**, a diffusing material **432** interspersed with openings **434**, another material, or a combination of materials. The second optical element **410** can reduce the contrast between the TDD **10** and the ceiling surfaces **15** and/or walls **13** surrounding the TDD **10** by further diffusing light E**1**, F**1**, G**1** exiting the TDD **10**. In certain embodiments, the first optical element **210** turns at least a portion of incident light E, F using a shaped reflective surface while the second optical element **410** spreads incident light E, F, G using refraction or photon diffusion. In some embodiments, the diffusing surfaces **420**, **426** are held in place or supported by supporting structures. The supporting structures can be constructed from any suitable material and can include rings **424**, **426**, rods **428**, other structural elements, or a combination of elements.

Example dimensions and proportions of the TDD will now be discussed with reference to the embodiment shown in FIG. **7**. In some embodiments, the design of the TDD **10** is compact. For example, the width or diameter W**2** (width dimension) of the base **214** of the optical element **210** may be approximately equal to the width dimension W**1** of the tube **24**. In some embodiments, the width dimension W**2** of the base **214** is less than or equal to the sum of the width dimension W**1** of the tube **24** and a relative short distance (e.g., about one inch). In an example embodiment, the diameter W**2** of the base **214** is 21.25" when the diameter W**1** of the tube **24** is 21". Other suitable tube **24** and optical element **210** dimensions can be selected as appropriate to provide desired lighting and diffusion characteristics to the room **12**.

In certain embodiments, the optical element **210** extends a short distance L**2** from the ceiling **14** into the room **12**. For example, the distance L**2** between the ceiling **14** and the base **214** of the optical element **210** can be at least about six inches and/or less than or equal to about twelve inches, less than or equal to about twelve inches, or less than or equal to about nine inches. In some embodiments, the optical element **210** extends at least partially into the tube **24**. For example, if the height L**1** of the optical element **210** is 8.85" and the distance L**2** between the base **214** of the optical element **210** and the ceiling **14** is 6.5", then the optical element **210** will extend 2.35" into the tube. By positioning the optical element **210** at least partially into the tube **24**, the distance between the base **214** of the optical element **210** and the ceiling **14** can be decreased.

At least some of the embodiments disclosed herein may provide one or more advantages over existing daylighting systems. For example, certain embodiments effectively allow a TDD to distribute light exiting the TDD onto the upper and lower regions of a room (e.g., the ceiling, walls, and/or floor). As another example, some embodiments provide techniques for allowing substantially light transmission directly beneath a TDD and to the sides of the TDD. As another example, certain embodiments provide an indirect diffuser that also allows a portion of incident light to transmit directly through the diffuser. As another example, some embodiments provide an indirect diffuser that provides substantial illumination directly below the diffuser and has reduced contrast between the base of the diffuser and an illuminated ceiling.

Discussion of the various embodiments disclosed herein has generally followed the embodiments illustrated in the figures. However, it is contemplated that the particular features, structures, or characteristics of any embodiments discussed herein may be combined in any suitable manner in one or more separate embodiments not expressly illustrated or described. For example, it is understood that a diffuser can include multiple optical elements, reflective surfaces, and/or diffusing surfaces. In many cases, structures that are described or illustrated as unitary or contiguous can be separated while still performing the function(s) of the unitary structure. In many instances, structures that are described or illustrated as separate can be joined or combined while still performing the function(s) of the separated structures. It is further understood that the diffusers disclosed herein may be used in at least some daylighting systems and/or other lighting installations besides TDDs.

It should be appreciated that in the above description of embodiments, various features are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that any claim require more features than are expressly recited in that claim. Moreover, any components, features, or steps illustrated and/or described in a particular embodiment herein can be applied to or used with any other embodiment(s). Thus, it is intended that the scope of the inventions herein disclosed should not be limited by the particular embodiments described above, but should be determined only by a fair reading of the claims that follow.

What is claimed is:

1. A daylighting apparatus comprising:

an internally reflective tube configured to direct daylight from a first end of the tube and a second end of the tube opposite the first end; and

a diffuser positioned at the second end of the tube, the diffuser comprising a first optical structure configured such that, when the day lighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room:

a reflected portion of the daylight is directed towards at least one ceiling or upper wall surface of the room; and

a transmitted portion of the daylight is directed towards at least one floor or lower surface of the room;

wherein the first optical structure comprises at least one reflective surface interrupted by a plurality of openings configured to permit at least some of the transmitted portion of the daylight to pass through the first optical structure.

2. The daylighting apparatus of claim 1, wherein the first optical structure comprises a reflective surface shaped and positioned to turn the reflected portion of the daylight.

3. The daylighting apparatus of claim 2, wherein the reflective surface comprises at least a first face configured to reflect collimated daylight at a first incident angle.

4. The daylighting apparatus of claim 3, wherein the reflective surface comprises at least a second face configured to reflect the collimated daylight at a second incident angle different from the first incident angle.

5. The daylighting apparatus of claim 2, wherein the reflective surface comprises at least a first curved face configured to reflect collimated daylight at a plurality of incident angles.

6. The daylighting apparatus of claim 2, wherein the reflective surface comprises a lower reflective face region, a middle reflective face region, and an upper reflective face region.

7. A daylighting apparatus comprising:

an internally reflective tube configured to direct daylight from a first end of the tube and a second end of the tube opposite the first end; and

a diffuser positioned at the second end of the tube, the diffuser comprising a first optical structure configured such that, when the daylighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room:

a reflected portion of the daylight is directed towards at least one ceiling or upper wall surface of the room; and

a transmitted portion of the daylight is directed towards at least one floor or lower surface of the room;

wherein the first optical structure comprises a reflective surface shaped and positioned to turn the reflected portion of the daylight;

wherein the reflective surface comprises a lower reflective face region, a middle reflective face region, and an upper reflective face region; and

wherein each of the lower reflective face region, the middle reflective face region, and the upper reflective face region comprises a conical frustum.

8. A daylighting apparatus comprising:

an internally reflective tube configured to direct daylight from a first end of the tube and a second end of the tube opposite the first end; and

a diffuser positioned at the second end of the tube, the diffuser comprising a first optical structure configured such that, when the daylighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room:

a reflected portion of the daylight is directed towards at least one ceiling or upper wall surface of the room; and

a transmitted portion of the daylight is directed towards at least one floor or lower surface of the room;

wherein the first optical structure comprises at least one aperture shaped and positioned to permit at least some of the transmitted portion of the daylight to pass through the first optical structure.

9. A daylighting apparatus comprising:

an internally reflective tube configured to direct daylight from a first end of the tube and a second end of the tube opposite the first end; and

a diffuser positioned at the second end of the tube, the diffuser comprising a first optical structure configured such that, when the daylighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room:

a reflected portion of the daylight is directed towards at least one ceiling or upper wall surface of the room; and

a transmitted portion of the daylight is directed towards at least one floor or lower surface of the room;

wherein the diffuser comprises a second optical structure configured to receive light exiting the first optical structure.

10. The daylighting apparatus of claim 9, wherein the second optical structure is configured to spread the reflected portion of the daylight.

11. The daylighting apparatus of claim 10, wherein the second optical structure is configured to spread the transmitted portion of the daylight.

12. A daylighting apparatus comprising:

an internally reflective tube configured to direct daylight from a first end of the tube and a second end of the tube opposite the first end; and

a diffuser positioned at the second end of the tube, the diffuser comprising a first optical structure configured such that, when the daylighting apparatus is installed with the first end positioned outside a room and the second end positioned to provide light to the room:

a reflected portion of the daylight is directed towards at least one ceiling or upper wall surface of the room; and

a transmitted portion of the daylight is directed towards at least one floor or lower surface of the room;

wherein the first optical structure comprises a reflective element generally in the shape of a frustum of a hyperboloid.

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