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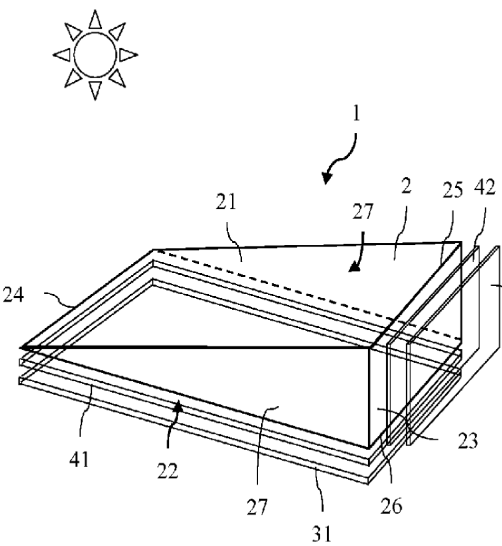
(54) **Title:** "OPTICAL CONCENTRATOR FOR FOUR-TERMINAL BIFACIAL PHOTOVOLTAIC MODULE".

Fig. 1



(57) **Abstract:** The present description concerns a photovoltaic module (1) and the method for installing the same. The photovoltaic module (1) comprises a light trapping optical concentrator (2). A first dichroic mirror (41) covers the bottom surface (22) of the concentrator (2), and is configured to transmit light in a first band, and to reflect light in a second band. A first photovoltaic cell (31) covers the first dichroic mirror (41) and is configured to generate electric power by conversion of light in the first band. A second photovoltaic cell (32) covers the rear surface (23) of the concentrator (2), preferably with a second dichroic mirror (42), and is configured to generate electric power by conversion of light in the second band. Characteristic of the photovoltaic module (1) is a wedge angle α selected for light in the second band to be guided by total internal reflection with a low concentrating ratio on the second photovoltaic cell (32) without the need of tilt sun tracking.

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Optical concentrator for four-terminal bifacial photovoltaic module

DESCRIPTION

Field of the invention

The present invention relates to the field of photovoltaic modules and a method of installing the module, according to the preamble of claims 1 and 11, respectively.

In more detail, the present invention relates to low-concentration four-terminal, preferably bifacial photovoltaic modules.

Particularly, but not exclusively, the photovoltaic modules can be used in utility scale plants, as well as along facade.

Background of the invention

Single junction photovoltaic cells are known to have a maximum efficiency given by the Shockley-Queisser limit. In order to increase efficiency beyond this limit, it is known how to manufacture photovoltaic modules with more junctions, that is more cells made of different materials and designed for optimal conversion of light in different frequency bands, such as infrared and visible light.

In some known examples, the two cells are overlapped and are electrically connected in series to each other. This imposes strong constraints on the design of the cells, since both cells of different materials must have the same area and work with the same current. Another strong constraint is that the top cell, namely the visible-light cell, must be transparent to light for the bottom cell, namely infrared light, in order for this light to reach the bottom cell.

To design around these constraints, other examples are known with spectral-splitting configurations. These use optical systems to lead light with different frequency bands upon different cells, which are neither overlapped nor connected in series, and may have different areas. Electric power is collected from the two cells with four electric terminals, namely two per cell.

One known drawback of spectral splitting solutions is that greater land occupation is generally required than for standard flat panels, which may affect the overall economic competitiveness of installing spectral splitting solutions in utility scale plants.

Other known solutions to increase efficiency of photovoltaic modules involve light concentrators, construed for example as lenses, mirrors or waveguides. This may save expensive material of the photovoltaic cell at expenses of more cheap material of the light concentrator.

A geometric concentration gain is the ratio of the inlet surface of the concentrator where light is received in input, to the outlet surface of the concentrator where light is output and received by the photovoltaic cell. Increasing the geometric concentration gain may increase or decrease conversion efficiency, depending on the material of the cell.

One known drawback of increasing concentration is the reduction of angular acceptance, according to the principle of conservation of étendue. Angular acceptance is a range of angles for which light incident on the concentrator will be led to the cell. Depending on the geometric concentration gain, acceptance may even fall below 1°. Therefore, high-concentration solutions require precise sun tracking mechanisms, which make the concentrator and the cell follow the movement of the sun.

Yet other known solutions to increase efficiency of photovoltaic modules involve bifacial cells. Commonly, one face of a photovoltaic cell receives sunlight directly. The opposite face, namely a back face, may or may not be designed to convert incident light too. The International Technology Roadmap for PhotoVoltaic (ITRPV) forecasts a market share for bifacial PV exceeding 30% by 2030.

Bifacial cells have the advantage that they may convert light diffusely reflected by an underlying ground surface, depending on its albedo. Light conversion at the back face is higher the more the underlying ground surface is lighted. In this regard, the module itself may cast some shadow on the ground, thereby reducing the albedo reflection. Thus, the geometry and height of the module determine some self-shadowing of the module and affect bifacial efficiency. It therefore brings economic advantages to develop geometries for bifacial modules that reduce the self-shading effect.

US 2010269885 describes photovoltaic devices, one of which including an optical guide shaped as a prism with an isosceles right triangle base, and two photovoltaic cells on one cathetus and on the hypotenuse.

Summary of the invention

One object of the present invention is providing a new photovoltaic module based on light concentration and spectral splitting, which has reduced impact of land use.

Another object of the present invention is increasing efficiency of a photovoltaic module with a concentrator, without the need to track sun movement.

Another object of the present invention is to reduce the shading effect of the photovoltaic module to increase efficiency when in bifacial operation.

These and other objects are achieved by a photovoltaic module and a method of installation thereof, according to any of the appended claims.

Advantages of the invention

The module of the invention has a wedge-shaped light-trapping and optical concentrator. Light is received from a top surface, and two different photovoltaic cells, best working in different frequency ranges, cover a bottom and a rear surface of the concentrator. Preferably, the top and rear surface are oriented at right angle, so that land use for spectral splitting is minimized. The bottom surface also has a dichroic mirror for reflecting the light which is best converted by the cell on the rear surface.

Thanks to the total internal reflection and the dichroic mirror, light in one frequency band is substantially not concentrated and converted at the bottom surface, while light in another frequency band is concentrated and guided for conversion to the rear surface. Therefore, the concentrator is considered asymmetric.

A limit condition is given for α being the wedge apex angle between top surface and bottom surface. It is to be noted that the trigonometric function $\tan\alpha$ is equal to the ratio of the area of rear surface divided by the area of top surface, that is also the inverse of the geometric concentration gain of concentrator. A first limit relation is $\frac{sin^2(\theta_{iMAX})}{2n^2} \leq \tan\alpha$, where $n = n_2/n_1$ and n_1 and n_2 are respectively the refractive index of the external medium and of the concentrator 2, and θ_{iMAX} is the desired angular acceptance. Typically, $n_1 \approx 1$, the external medium being air.

The limit condition is a thermodynamic limit condition set by the étendue theorem for the asymmetric concentrator, so that full optical energy at the input surface can be transferred in output at the rear surface and onto the solar cell therein. Preferably, the wedge angle has a tangent that is as close as possible to the limit tangent.

The concentrator may act as a waveguide by total internal reflection for light within the selected angular acceptance. By setting $\theta_{iMAX} = 46° 54'$, the angular acceptance is greater than the excursion of sun declination over a certain period of the year, such as the whole year or in other embodiments half a year.

Thus, as is explained in the Detailed Description section, the amplitude of wedge apex angle of concentrator 2 can be set so that its angular acceptance can accommodate the useful excursion of sun in the north-south direction. Therefore, upon properly setting the elevation angle of the top surface 21 with respect to the zenit, to track sun movement in the elevation angle during the year may be avoided, without much reducing efficiency.

This proper elevation setting for top surface 21 also typically casts a limited shadow effect with respect to the standard orientation of panels, and therefore is beneficial for bifacial operation of the cell at the bottom surface.

Highest design efficiency is achieved by making the wedge angle close to the limit condition. On the other side, a maximum wedge angle can be taken 45° for the concentrator 2 to have a geometric concentration gain greater than one. Preferred embodiments have wedge angle below narrower upper limits.

In advantageous embodiments, side surfaces of the concentrator are arranged at right angles to the top, bottom and rear surfaces. This ensures a high amount of total internal reflection also for light incident on the side surfaces. Accordingly, a good efficiency is obtained not only for directly irradiated light rays, but also for diffused light. Moreover, azimuthal sun tracking may also be avoided.

Brief description of the drawings

The present invention will now be described in more detail hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown.

FIG. 1 is a perspective exploded view of a photovoltaic module according to one embodiment of the invention,

FIG.s 2 and 3 are perspective views of the module of FIG. 1, with a representation of light rays upon a top surface with different orientations,

FIG. 4 is a perspective view of the module of FIG. 1, with a representation of albedo reflections for bifacial operation, and

FIG. 5 is a perspective view of the module of FIG. 1, with a representation of diffused light rays.

DETAILED DESCRIPTION

A photovoltaic module according to one embodiment of the invention is referenced 1 in the drawings.

The module 1 comprises an optical concentrator 2, which is shaped as a wedge, preferably as a triangular prism.

In more detail, the concentrator 2 has a top surface 21 for receiving incident light, and also a bottom surface 22 and a rear surface 23. Here, the terms top, bottom, rear and similar designate positions of the surfaces in one preferred use orientation of the concentrator.

The top, bottom and rear surfaces 21, 22, 23 are substantially planar. Thus, the concentrator 2 has a substantially triangular cross-section.

Nevertheless, the top surface 21 may be subject to known antiglare treatments, which may involve forming a surface roughness or application of antiglare chemical substances. Antiglare increases the amount of incident light that is transmitted in the concentrator 2, instead of reflected away.

In one embodiment, the top surface 21 is covered with solar control glass 28, preferably having substantially the same refractive index as the concentrator 2.

The top, bottom and rear surfaces 21, 22, 23 are connected at respective edge portions 24, 25, 26. Namely, the top surface 21 and the bottom surface 22 are connected at a front edge portion 24, the top surface 21 and the rear surface 23 are connected at a top rear edge portion 25, while the bottom surface 22 and the rear surface 23 are connected at a bottom rear edge portion 26.

In preferred embodiments, the top surface 21 and the rear surface 23 form a top rear angle at the top rear edge portion 25, that is at least substantially a right angle, preferably substantially equal to a right angle. Thus, the top rear angle is preferably right, but it can also be obtuse. Here, substantially equal means that only small deviations may be tolerated, such as up to 5°, preferably only up to 2°.

It is worthwhile noting that the concentrator 2 also has two opposite side surfaces 27. In the preferred prism embodiment, the side surfaces 27 are parallel to each other and form substantially right angles with each of the top, bottom and rear surfaces 21, 22, 23, with advantages that are mentioned below.

The concentrator 2 is a full body made of a transparent material. In test examples, the concentrator 2 is made of polymethyl methacrylate (PMMA) or polyurethane resins.

In preferred embodiments, a refractive index n_2 of the concentrator 2 is at least 1.4, preferably below 2. For example, the above materials have a refractive index n_2 between 1.5 and 1.6. Currently, materials with higher refractive indexes n_2 may be more expensive or may be suboptimal as less transparent, but there is no limitation to use materials with higher refractive indexes n_2 that already exist or may become available in the future.

In the following, reference will be made to an absolute refractive index n_2 of the concentrator 2, to an absolute refractive index n_1 of the medium in which the concentrator 2 is arranged, namely air, and to a relative refractive index n of the concentrator, being n_2/n_1. Some of the physical laws used herein strictly require the use of one of the absolute and relative indexes of the concentrator 2, but since $n_1 \approx 1$, in practice n and n_2 can be used substantially interchangeably.

The module 1 comprises a first photovoltaic cell 31, covering most of the bottom surface 22 of the concentrator 2, and a second photovoltaic cell 32 covering most of the rear surface 23 of the concentrator 2.

Here, an element covering most of a surface may be understood as the element covering the whole surface or a major part thereof, such as more than 80% of the surface. Reducing the area covered by the cells 31, 32 usually means reducing power output. However, as is known to the skilled person, small regions close to an edge portion, such as a small portion of the bottom surface 22 adjacent to the front edge portion 24, may be shadowed due to refraction effects at the front edge portion 24, depending on orientation of light rays. Thus, the first cell 31 may not extend up to the front edge portion 24, in order not to cover the shadowed area for at least some orientations of the light rays. A cell 31, 32 covering a shadowed area may or may not have a negative impact on power conversion, depending on the material of the cell 31, 32.

The first photovoltaic cell 31 is configured to generate electric power by conversion of incident light, mainly in a first frequency band, while the second photovoltaic cell 32 is configured to generate electric power by conversion of incident light, mainly in a second frequency band, disjointed from the first frequency band. The concentrator 2 is transparent at least in the first and second frequency bands. Thus, the relevant light may propagate in the concentrator 2 to reach the first and second cells 31, 32.

It is to be noted that any photovoltaic cell generally converts light in electric power with different efficiencies based on its material and on the frequency of light. Therefore, different cells made of different materials will have maximum conversion efficiency for different light frequencies. Here, a cell is considered to mainly convert power in a certain frequency band, where the instant band is a range of frequencies for which conversion efficiency is maximum or over a predetermined threshold.

Therefore, the first and the second cells 31, 32 are preferably made of different materials. In the preferred embodiment, the first frequency band has lower frequencies then the second frequency band. In more detail, the first frequency band is a near-infrared band and the first cell 31 is a silicon cell. Moreover, the second frequency band is a visible-light band and the second cell 32 is a hybrid perovskite cell, also called high bandgap cell. However, one or both the first and second cells 31, 32 may be selected with different materials, as already known or yet to be developed.

One advantage of the material selection above is that a cheaper material is selected for the first cell 31 and a more expensive material for the second cell 32. In fact, as described below, the second cell 32 has a lower surface area than the first cell 31. As is known, typically, technological constraints do not allow to manufacture low-cost, high-performance, high bandgap cells as wide as a standard silicon cell.

It is to be noted that cells 31, 32 are usually suitable to convert some light also with frequencies above their main conversion frequency band, though with a lower efficiency. Instead, cells 31, 32 are usually unsuitable to convert light with frequencies below their main conversion frequency band, as each photon carries a lower energy than the cell material bandgap.

Thus, despite the first cell 31 mainly converts in the first frequency band, it may still be adapted to convert some light also in the second frequency band, though with a lower efficiency than the second cell 32.

The module 1 comprises a first dichroic mirror 41 and preferably also a second dichroic mirror 42.

The first dichroic mirror 41 covers most of the bottom surface 22 of the concentrator 2, and is arranged between the bottom surface 22 and the first cell 31. Thus, the first cell 31 forms a layer which does not directly lay on the bottom surface 22, but on the first dichroic mirror 41, which in turn forms a layer that may lay directly on the on the bottom surface 22.

The first dichroic mirror 41 is configured to mainly transmit light in the first frequency band, and to mainly reflect light in the second frequency band. Here, the terms mainly reflect and mainly transmit mean that, in the relevant frequency band, more light is reflected than transmitted, or the other way round, respectively.

The first dichroic mirror 41, as well as the second dichroic mirror 42 described below, can be made of alternated thin layers of dielectric materials as can be designed and fabricated by skilled people in the art. Silicon dioxide and Titanium dioxide are examples of such materials. In a test example dichroic mirrors are selected with a cutoff frequency of 735 nm, with a 0% to 100% spectral selection within 2 nm of transition.

Thanks to the first mirror 41, light in the first frequency band, if reaching the bottom surface 22 after entering the concentrator 2 through the top surface 21, will be mainly transmitted to the first cell 31 and converted with high efficiency. At the same time, light in the second frequency band following the same path will only minorly reach the first cell 31 and converted with low efficiency, but will be mainly reflected and remain in the concentrator 2 (rays R12, R13), in order to reach the second cell 32 as described below and be converted with high efficiency.

Similarly, the second dichroic mirror 42, if provided, covers most of the rear surface 23 of the concentrator 2, and is arranged between the rear surface 23 and the second cell 32. In case there is no second mirror 42, the second cell 32 may form a layer laying directly on the rear surface 23.

The second dichroic mirror 42 is configured to mainly transmit light in the second frequency band, and to mainly reflect light in the first frequency band (rays R22, R23), for a part of light in the first frequency band to lastly reach the first cell 31. First mirror 41 and second mirror 42 can be respectively named hot mirror and cold mirror, in that they reflect respectively the second frequency band and the first frequency band.

The second mirror 42 is less important than the first mirror 41 in view that, as already mentioned, the surface area of the rear surface 23 is lower than the surface area of the bottom surface 22. Besides, the portion of incoming light in the first frequency band that directly reaches the rear surface is a small fraction of the total. Thus, only a minor amount of light is expected to be reflected by the second mirror 42 for reaching the first cell 31. Experimental tests showed that the second mirror 42 may increase efficiency, but just by 3%.

It will be evident to the skilled person that light in the second frequency band reflected by the first dichroic mirror 41 can be at a first limit angle R13, so that it undergoes total internal reflection upon reaching surface 21 and be directed to the rear surface 23. Or, light can be furtherly reflected by the first mirror 41 at a wider angle than R13, which also undergoes total internal reflection upon reaching surface 21, so that finally light is directed to the rear surface 23.

It is known to skilled people that a reference angle of incidence for light and a required angular acceptance are design parameters of multilayered dielectric dichroic mirrors. It is also known that, in case of hot mirror 41, the transition frequency increases for incidence angles wider than the reference angle. Therefore, by properly choosing the reference design frequency for the first mirror 41 according to a first limit angle R13, light in the first frequency band is finally directed to rear surface 23. Similarly, the second mirror 42 can be designed for incidence at 0° and with maximized angular acceptance by people skilled in the art.

In one aspect of the invention, the top surface 21 and the bottom surface 22 form an acute wedge angle α that is selected, depending on the relative refractive index n, for the concentrator 2 to properly act as a waveguide over the year. In more detail, the tangent of the wedge angle α, in case of the top rear angle being right and the concentrator 2 being a triangular prism, is also the ratio of the rear surface 23 to the top surface 21, that is a reciprocal of a geometric concentration gain for light in the second frequency range to reach the second cell 32.

Here and in the following, terms as tangent, sine, cosine and abbreviations thereof will be intended to mean the well-known trigonometric functions. Similarly, abbreviations using the apex $^{-1}$ after a trigonometric function will be intended to mean the inverse of the instant trigonometric functions, namely arcsine, arccosine and arctangent.

It is to be noted that, while light in the second frequency band is concentrated with a geometric concentration gain greater than 1, when considering transmission of light in the first frequency band to the first cell 31, there can be substantially no concentration, that is a surface area ratio of the top surface 21 to the bottom surface 22 close to one, or even lower than one.

One design criterion for the wedge angle α is that it is not greater than 45°. In fact, since preferred embodiments have a right angle as the top rear angle, wedge angles α above 45° would cause the concentrator to no more concentrate light in the second frequency band.

As an additional criterion, the wedge angle α is selected in order for a portion of light rays to be confined in the concentrator 2 by total internal reflection at the top surface 21.

In more detail, as is known to the skilled person and shown in figures 2 and 3, the refractive index n of the concentrator 2 determines light rays to be deflected upon entering the concentrator 2 through the top surface 21 (see rays R11, R12 in figure 2, and rays R21, R22 in figure 3). Then, light rays may reach the bottom or rear surface 22, 23, mostly the bottom surface 22, depending on the orientation and entry position of light rays.

A part of these light rays on the bottom surface 22, mainly in the second frequency band, is then reflected (rays R12, R13) by the first mirror 41 with a certain direction ultimately related to the wedge angle α, and may reach the rear surface 23 or may strike back on the top surface 21 from inside the concentrator 2. Depending again on the orientation of light rays and on the refractive index n, the part of light rays reaching the top surface 21 from inside the concentrator 2 may be subject or not to a total internal reflection phenomenon (rays R13, R14). If yes, light rays in the second frequency band may be reflected again a certain number of times, but they will inevitably reach the rear surface 23 and the second cell 32. If not, some light will exit the concentrator 2 from the top surface 21, reducing the efficiency of the module 1.

Thus, the total internal reflection phenomenon for the part of light rays reflected by the first mirror 41 and reaching the top surface 21 from inside the concentrator 2 is strictly determined by the incidence angle of the light rays, and by properties of the concentrator 2, that are the refractive index n and the wedge angle α. The incidence angle is considered as the angle formed between the orientation of light rays and a normal to the top surface 21.

In more detail, as known to the skilled person, for light rays R_{13} reaching the top surface 21 from inside the concentrator 2, total internal reflection occurs if their angle with the normal to the top surface 21 is at least a limit angle for total internal reflection being $\theta_L = \sin^{-1}({}^{n_1}/_{n_2})$. Based on this limit condition for light rays R_{13}, a corresponding limit condition on light rays R_{11} entering the concentrator 2 through the top surface 21 can be determined for total internal reflection to occur thereafter.

In particular, once a concentrator 2 has been manufactured, total internal reflection occurs for light rays that entered through the top surface 21 at an incidence angle θ_i with respect to the surface normal greater than a predetermined minimum incidence angle limit value θ_{iL} such that $\sin\theta_i \geq \sin\theta_{iL} = n\sin(\theta_L - 2\alpha) = \cos(2\alpha) - \sin(2\alpha)\sqrt{n^2 - 1}$.

A first limit condition for the wedge apex α angle is set by $\theta_{iL} = 0$ so that light in the second frequency band at any positive angle of incidence is trapped in concentrator 2 by total internal reflection. In this first limit case the condition becomes

$\tan(2\alpha) = 1/\sqrt{n^2 - 1}$, or equivalently $\alpha = \frac{1}{2}\sin^{-1}\left(\frac{1}{n}\right)$. In a reference case of n=1.5, the above condition leads to the limit: $\alpha = 24°6'$ and to a condition on geometrical concentration $C_G = 1/\tan\alpha = 2{,}23$.

This condition determines total internal reflection for a wide range of incidence angles θ_i, namely over an entire right angle. However, depending on latitude and on installation conditions of the module 1, as discussed below, sun rays may never be perpendicular to the top surface 21.

Accordingly, the geometrical concentration gain can be increased and the wedge apex angle α decreased below the above limit case, at the expense of effective light confinement and not indefinitely, since θ_{iL} increases accordingly. In the limit case of infinite geometric concentration gain, $\alpha = 0, \sin\theta_{iL} = 1$ and $\theta_{iL} = 90°$, meaning that for no angle of incidence can light in the second band be guided at the rear surface of the wedged prism. Nevertheless, applicants have demonstrated that θ_{iL} can be increased according to the location of installation of the photovoltaic module, while maintaining an overall optical performance ratio of the module above 80% on a wide angular extension of incident sunlight.

On the other side, decreasing the geometrical concentration gain and increasing the wedge apex angle α compared to the above limit case would cause θ_{iL} to be negative. This means that total internal reflection is achieved also for light rays reaching the top surface 21 with particular orientations from the rear. However, this is not useful for guiding directly incident sun rays, which are expected to come from the southern direction (i.e. $\theta_{iL} > 0$), and at the same time the geometric concentration gain is decreased, with more use of expensive material for the second cell 32, and technologic dimensional constraints. Therefore, it is preferred that $\alpha \leq \frac{1}{2}\sin^{-1}\left(\frac{1}{n}\right)$.

On decreasing the tangent of the wedge angle α below this limit angle, concentration is increased, the angular acceptance range is narrower than the threshold angle and the minimum incidence angle θ_{iL} widens. Instead, on increasing the tangent, acceptance widens and the minimum incidence angle θ_{iL} is reduced, but concentration is generally lower, and so more expensive material is required for the second cell 32.

A second limit to the geometric concentration gain, that is the inverse of the tangent of the apex angle of the wedge in concentrator 2, is the thermodynamic limit condition set by the étendue theorem for the asymmetric concentrator, imposing that optical energy at the input surface can be totally transferred in output at the rear surface 23 and onto the solar cell 32 therein, with no mentioning of the unavoidable additional optical loss due to finite absorbance of the real optical medium and finite scattering and possible reflections at the interfaces.

Accordingly, a limit tangent relation is $\tan\alpha \geq \frac{sin^2(\theta_{iMAX})}{2n^2}$. Angle θ_{iMAX} is the maximum acceptange angle for asymmetric irradiation, measured from the top surface 21, compatible with conditions of use of the photovoltaic module 1 in preferred installation conditions.

As known, as long as light rays are oriented within the angular acceptance range, they will be concentrated as desired based on the geometric concentration gain. Instead, when light rays are oriented outside the angular acceptance range, some of them may still reach the output surface of the concentrator 2, here the rear surface 23. However, the whole incident light will not be concentrated based on the geometric concentration gain, but on a smaller effective concentration gain.

In the limit of $\theta_{iMAX} = 90°$ the condition on wedge apex angle α becomes the condition for limit tangent $\tan\alpha \geq \frac{1}{2n^2}$. In a reference case of n=1.5, the above condition leads to the limit: $\alpha \geq 12°53'$ and to a condition on geometrical concentration $C_G = 1/\tan\alpha \leq 4.5$.

While setting θ_{iMAX} at least as 90° is preferred, depending on the intended installation conditions the geometric concentration gain can be made higher and the tangent to the wedge angle α can be reduced, by selecting operating conditions so that $\theta_{iMAX} < 90°$.

Applicants have demonstrated that optical concentrator 2 with proper $\tan\alpha$ value and refractive index n can be designed, which couples with solar cells 31, 32 of optimized dimensions and performance in energy conversion efficiency for the second frequency band, while maintaining an angular acceptance at least equal to $46°\ 54'$ being $46°\ 54'$ the angular difference in sun elevation between the summer and winter solstice, which is independent on latitude of installation. Thus, the minimum angular acceptance accepted for at least one latitude is for θ_{iMAX} equal to $46°\ 54'$, and wedge angle α satisfying $\tan\alpha \geq \frac{sin^2(\theta_{iMAX})}{2n^2}$.

The threshold angle of 46° 54’ is selected as the annual excursion of the declination of the sun, namely between summer solstice and winter solstice. Thus, with the limit tangent for the wedge angle α and a proper orientation of the concentrator 2, total internal reflection may occur for all light rays at noon both in the summer solstice and in the winter solstice, as well as in any intermediate condition. In another embodiment, the angular acceptance is wide enough to be equal to the sum of θ_{iL} and the elevation of the sun at the summer solstice, at selected latitude of installation.

Therefore, a preferred range of admissible values for the apex angle of the concentrator 2 that satisfies both limit conditions is expressed by the following relation: $\tan^{-1}\left(\frac{sin^2(\theta_{iMAX})}{2n^2}\right) \leq \alpha \leq \frac{1}{2}\sin^{-1}\left(\frac{1}{n}\right)$. The concentration can be increased from the lower limit value set by condition $\theta_{iL} = 0$ up to reach the thermodynamical limit, by admitting $\theta_{iL} > 0$. In particular, the preferred values of the tangent of the wedge angle α are only slightly higher that the thermodynamic limit tangent, namely in the range described above.

In a test example with cell 31 of silicon and cell 32 of hybrid perovskite thin film, a geometrical value of 4 has been selected, to cope with technological constraints of the solar cell 32, so that $\alpha = \tan^{-1}(1/4) = 14\,deg.$ Given $n_2 = 1.5$ it results $\theta_{iL} \approx 21\,deg$.

The top limit of the above range is preferably further reduced to $\alpha \leq \frac{1}{2}\left[\sin^{-1}\left(\frac{1}{n}\right) - \sin^{-1}\left(\frac{\cos(\theta_{iMAX})}{n}\right)\right]$. With this limit, θ_{iL} will be greater than 0, and in particular, it will be the complementary to θ_{iMAX}. Upon selecting an optimal θ_{iMAX} based on latitude, the above condition allows for horizontal installation of the top surface 21. Lower values of the wedge angle α will require a rearward tilt installation, and higher values of the wedge angle α may be installed also with a forward tilt installation.

It has to be noticed that in module 1 there is a portion of light in the second frequency band that reaches rear surface 23 and cell 32, subject to laws of optical refraction without being trapped nor concentrated. This portion of light contributes to solar energy conversion in the first frequency band for incidence light angles beyond the angular acceptance for concentrator 2. A first portion of light in the second frequency band directly reaches rear cell 32 that is light incident on top surface 21 at a distance to rear surface 23 such that light meets surface 23 before being reflected at surface 21, independently of the incidence angle. A second portion of light in the second frequency band directly is light incidence on top surface 21 at a distance to rear surface 23 such that light meets surface 23 upon being reflected at surface 22 but before reaching top surface 21 and therefore without the need to undergo total internal reflection at top surface 21. Skilled person can compute the specific distances to rear surface 23 for these first and second conditions to happen at each possible angle of incidence.

Increasing the top right angle as an obtuse angle may be accepted, as it does not change effective concentration and efficiency, but requires more material for the second cell 32. Reducing the top right angle as an acute angle is not preferred as it may cause some light in the first frequency range to be reflected by the second mirror 42, reach the top surface 21, but not be subject to total internal reflection and exit the concentrator 2, despite entering in the acceptance range for light in the second frequency band.

Advantageously, the concentrator 2 may be installed in a fixed position and remain highly efficient throughout the year. In this case, the concentrator 2 should be preferably installed with the rear surface 23 spaced from the front edge portion 24 in a North-South azimuthal orientation, with the front edge portion 24 closer to the Equator than the rear surface 23, namely toward South if in the Boreal Hemisphere.

Alternatively, the sun position may be daily tracked in the East-West direction, that is azimuthally tracked, by rotating the concentrator 2 about a vertical axis, but there is no need to track sun movement in the North-South direction, that is tracked in elevation. With daily tracking, the above described North-South azimuthal orientation is daily fulfilled substantially at noon.

In both cases of fixed position and azimuthal tracking, top surface 21 is kept with a constant elevation angle, also named tilt angle. Nevertheless, nothing prevents use of the module 1 with elevation sun tracking, to achieve even higher efficiencies, despite at higher costs.

The elevation angle β of module 1 can be measured as the angle of the top surface 21 to an ideal horizontal surface, not necessarily being a real ground surface. The elevation angle, measured with respect to the horizontal and starting from the north direction, is also equal to the angle between the zenit and the direction normal to the top surface 21. In case of tilted ground, the elevation angle can still be defined as the angle between the zenit and the normal to the top surface 21.

In case of stationary alignment of the module in the north-south direction, the elevation angle is preferably set as β =(90°-($\phi_e + \theta_{iL}$)), being ϕ_e the maximum sun declination at summer solstice at the latitude of installation. Alternatively, a couple of different values β_s and β_w for tilt angle can be defined and the module 1 can be repositioned twice a year, typically corresponding to equinoxes.

The Applicant surprisingly found that, in case the side surfaces 27 are substantially perpendicular to the top, bottom and rear surfaces 21, 22, 23, it can be demonstrated that also light rays entering the concentrator 2 through the side surfaces 27 will be subject to total internal reflection and confined in the concentrator 2 until reaching the first and/or second cells 31, 32, at condition that the refractive index n is at least 1.4. More precisely, the refractive index n_2 of the concentrator 2 should be at least square root of two times the refractive index n_1 of the surrounding medium, namely air.

Accordingly, daily azimuthal tracking still provides some increase in efficiency, but is not necessary for an acceptable efficiency.

In case of side surfaces 27 not being exactly perpendicular to the other surfaces 21, 22, 23, some tolerance may be admitted, with more tolerance for higher refractive indexes n.

Moreover, the overall performance of the module is contributed also by light in the first frequency band, which is not subject to concentration and limitations in angular admittance.

In the described test example, an optical efficiency for direct irradiation of the solar spectrum is above 80% over the whole acceptance range, with a maximum of 88% for an optimal incidence angle. As incidence angles is decreased below the limit incidence angle for total internal reflection, optical efficiency gradually decreases down to a limit value of about 48%. For angles of incidence beyond the optical acceptance optical efficiency also decreases gradually to about 57% at 80° of incidence.

Moreover, an optical efficiency for isotropically diffused light is 62%, given by the sum of 45% in the first frequency band and 17% in the second frequency band. An example of diffused light rays R4 is shown in figure 5.

In preferred embodiments, the first cell 31 is a bifacial photovoltaic cell. Bifacial cells are known to be configured to convert in electric power light received from opposed faces of the cell.

Advantageously, when the module 1 is installed in the position ensuring total internal reflection, as mentioned above and further detailed below, in view of its peculiar requirements on tilt the module 1 casts a smaller shadow on any underlying ground surface than a standard flat panel of the same extension of the top surface properly oriented according to the state of the art. Therefore, a significant amount of solar light may reach the ground surface, be diffusely reflected and reach the rear face of first cell 31.

Optionally, even the second cell 32 may be a bifacial photovoltaic cell.

Figure 4 shows light rays R31 reaching directly the top surface 21, light rays R32 reaching the ground surface, and light rays R33 reflected by the ground surface toward the rear face of first cell 31.

A method of installing and/or operating the module 1 is now described.

The concentrator 2 is mounted to a support (not shown), which can be a fixed support or a movable support. In case of a fixed support, the concentrator 2 is kept in a fixed, predetermined position all day long. In this position, the rear surface 23 is spaced from the front edge portion 24 in a North-South orientation, with the front edge portion 24 closer to the Earth Equator than the rear surface 23.

Instead, a movable support may comprise a motor configured to daily rotate the concentrator 2 about a vertical axis to track azimuthal sun movement, thereby deviating from the Nort-South orientation. Namely, the concentrator 2 will assume substantially at noon the same predetermined position as in the case of a fixed support.

As azimuthal rotation occurs about a vertical axis, the concentrator 2 is held by the support such that the top surface 21 is arranged with a constant elevation angle. Of course, the elevation angle is constant also in case of a fixed support.

The elevation angle is selected with different values for different geographic locations, based on their latitudes, for sun rays to fall in the angular acceptance range at least at noon of each day of a desired year period, preferably the whole year, or a part of the year such as half year. In the latter case, the concentrator 2 can be rearranged with different elevation angles in different year periods to maximize efficiency in all of them. In more detail, the concentrator 2 can be arranged with different elevation angles, on the same support or on different supports.

Based on latitude, sun rays are oriented with a first direction in a maximum sun height day of the chosen year period, that is summer solstice in case the whole year is considered. Moreover, sun rays are oriented with a second direction in a minimum sun height day of the chosen year period, that is winter solstice in case the whole year is considered.

For each embodiment of the concentrator 2, the angular acceptance range for concentrating light in the second spectral band is delimited by a maximum incidence angle and a minimum incidence angle θ_{iL} . In the test example, the minimum incidence angle is 21°, and below it there is no total internal reflection.

Thus, the elevation angle is preferably set as (90°-($\phi_e + \theta_{iL}$)), or slightly lower, being θ_{iL} the minimum incidence angle and ϕ_e the maximum sun declination at summer solstice at the latitude of installation. The minimum incidence angle can be calculated by the skilled person, as described above about θ_{iL} , for that part of light rays in the second frequency band, entering the concentrator 2 through the top surface 21, being reflected by the first dichroic mirror 41, and reaching again the top surface 21 from inside the concentrator 2, to be subject to total internal reflection.

In case the maximum sun declination at summer solstice and the minimum incidence angle sum to 90°, the tilt angle is zero. This applies for the wedge angle as described above, equal to $\alpha = \frac{1}{2}\left[\sin^{-1}\left(\frac{1}{n}\right) - \sin^{-1}\left(\frac{\cos(\theta_{iMAX})}{n}\right)\right]$.

For example, for a geographic location at 45° latitude north, such as in Lombardy, Italy, the elevation angle for the test example is substantially horizontal, that is close to 0°. For latitudes below 45°, in the test example the maximum sun declination at summer solstice and the minimum incidence angle sum to more than 90° so that the tilt angle is below 0° and the top rear edge portion 25 will be arranged at a lower position than the front edge portion 24.

It is apparent that negative elevation angles will cause the module 1 to cast only a very small shadow on the ground. It is to be noted that the support may sustain the module 1 at a predetermined height above the ground surface. Increasing this height to a certain extent may further reduce shadow on the ground. The optimal height may be determined by the skilled person, and may be in the order of 1 m.

Alternatively, the module 1 may also be installed on a support fixed to a substantially vertical post or surface, such as a building façade.

CLAIMS

1. A photovoltaic module (1), comprising:

- a transparent wedge-shaped optical concentrator (2), with a predetermined refractive index n, that is at least 1.4, the concentrator (2) having:

    - a top surface (21) for receiving incident light,

    - a bottom surface (22), connected to the top surface (21) at a front edge portion (24), the top surface (21) and the bottom surface (22) forming a wedge angle α,

    - a rear surface (23) connected to the top surface (21) at a top rear edge portion (25), and to the bottom surface (22) at a bottom rear edge portion (26),

- a first dichroic mirror (41) covering most of the bottom surface (22) of the concentrator (2), and configured to mainly transmit light in a first frequency band, and to mainly reflect light in a second frequency band,

- a first photovoltaic cell (31) covering most of the bottom surface (22) of the concentrator (2), the first dichroic mirror (41) being arranged between the bottom surface (22) and the first cell (31), the first cell (31) being configured to generate electric power by conversion of incident light, mainly in the first frequency band, and

- a second photovoltaic cell (32) covering most of the rear surface (23) of the concentrator (2), the second cell (32) being configured to generate electric power by conversion of incident light, mainly in the second frequency band,

- wherein the following relation is verified for the wedge angle α and the refractive index n of concentrator (2): $\tan^{-1}\left(\frac{sin^2(\theta_{iMAX})}{2n^2}\right) \leq \alpha$, where $\theta_{iMAX} = 46° \ 54'$, and

characterized by the fact that a geometric concentration gain, being a ratio between a surface area of the top surface (21) to a surface area of the rear surface (23), is at least 2.

2. The module (1) of claim 1, wherein $\tan\alpha \geq \frac{1}{2n^2}$.

3. The module (1) of claim 1 or 2, wherein $\alpha \leq \frac{1}{2}\sin^{-1}\left(\frac{1}{n}\right)$.

4. The module (1) of claim 3, wherein $\alpha \leq \frac{1}{2}\left[\sin^{-1}\left(\frac{1}{n}\right) - \sin^{-1}\left(\frac{\cos(\theta_{iMAX})}{n}\right)\right]$.

5. The module (1) of any claim from 1 to 4, wherein the top surface (21) and the rear surface (23) form a top rear angle that is at least substantially a right angle, preferably substantially equal to a right angle.

6. The module (1) of any claim from 1 to 5, wherein the geometric concentration gain is lower than 6, preferably between 3.6 and 4.

7. The module (1) of any claim from 1 to 6, wherein the refractive index n is below 2.

8. The module (1) of any claim from 1 to 7, wherein the wedge angle α is between 7° and 23°.

9. The module (1) of any claim from 1 to 8, wherein the concentrator (2) has two opposite side surfaces (27), parallel to each other and forming substantially right angles with each of the top, bottom and rear surfaces (21, 22, 23).

10. The module (1) of any claim from 1 to 9, comprising a second dichroic mirror (42) covering most of the rear surface (23) of the concentrator (2), the second dichroic mirror (42) being arranged between the rear surface (23) and the second cell (32), and being configured to mainly transmit light in the second frequency band, and to mainly reflect light in the first frequency band.

11. The module (1) of any claim from 1 to 10, wherein the first frequency band has lower frequencies then the second frequency band, preferably wherein the first frequency band is a near-infrared band and/or the second frequency band is a visible light band.

12. The module (1) of any claim from 1 to 11, wherein the first cell (31), and optionally also the second cell (32), is a bifacial photovoltaic cell.

13. A method of installing a photovoltaic module (1), comprising:

- providing a photovoltaic module (1) according to anyone of claims 1 to 12;
- providing a support for supporting the photovoltaic module (1);
- mounting the photovoltaic module (1) to the support, such that the top surface (21) is arranged with a constant elevation angle all day long, and such that, at least at noon, the rear surface (23) is spaced from the front edge portion (24) in a North-South orientation, with the front edge portion (24) closer to the Equator than the rear surface (23).

14. The method of claim 13, wherein the support is configured to keep the concentrator (2) in a fixed position all day long, or to daily rotate the concentrator (2) about a vertical axis.

15. The method of claim 13 or 14, wherein:

- the module (1) is installed in a predetermined geographic location for a predetermined year period, preferably the whole year,

- in the geographic location, sun rays are oriented with a first direction at noon in a maximum sun height day of the predetermined year period, preferably summer solstice, and with a second direction at noon in a minimum sun height day of the predetermined year period, preferably winter solstice, and

- the elevation angle of the top surface (21) is so selected that an angle between a normal to the top surface (21) and the first direction is substantially equal or greater than a predetermined minimum incidence angle limit value θ_{iL}, for which $\sin\theta_{iL} = \cos(2\alpha) - \sin(2\alpha)\sqrt{n^2 - 1}$.

16. The method of claim 15, wherein the module (1) is installed in the predetermined geographic location with different elevation angles for different year periods.

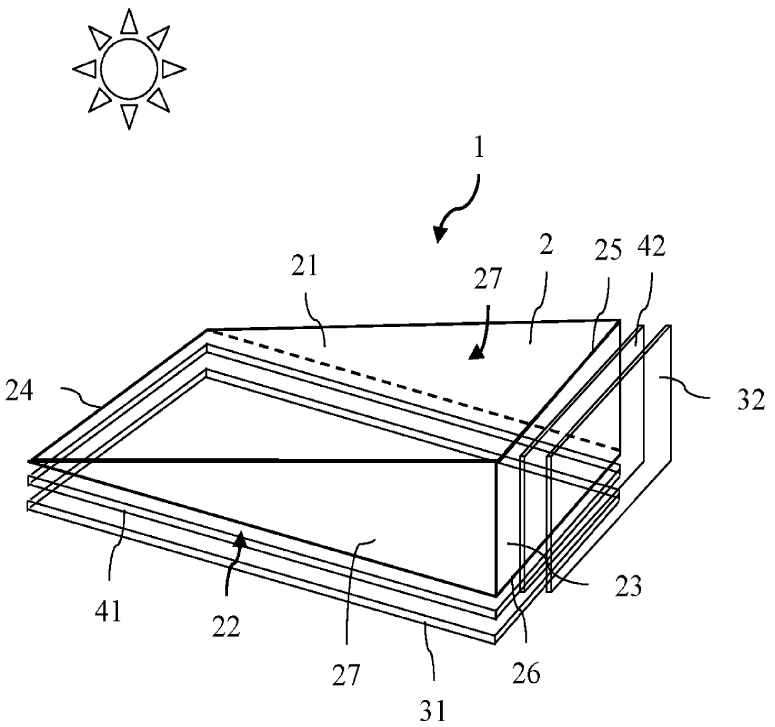

Fig. 1

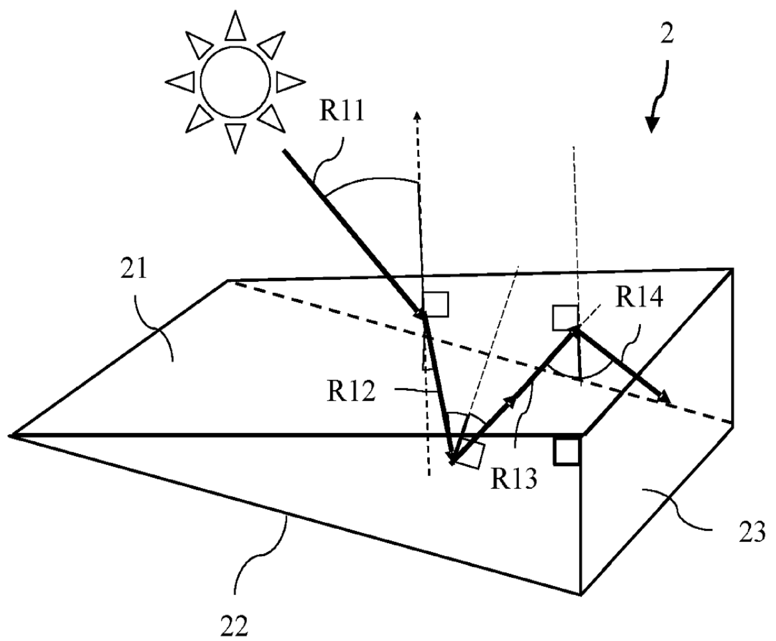

Fig. 2

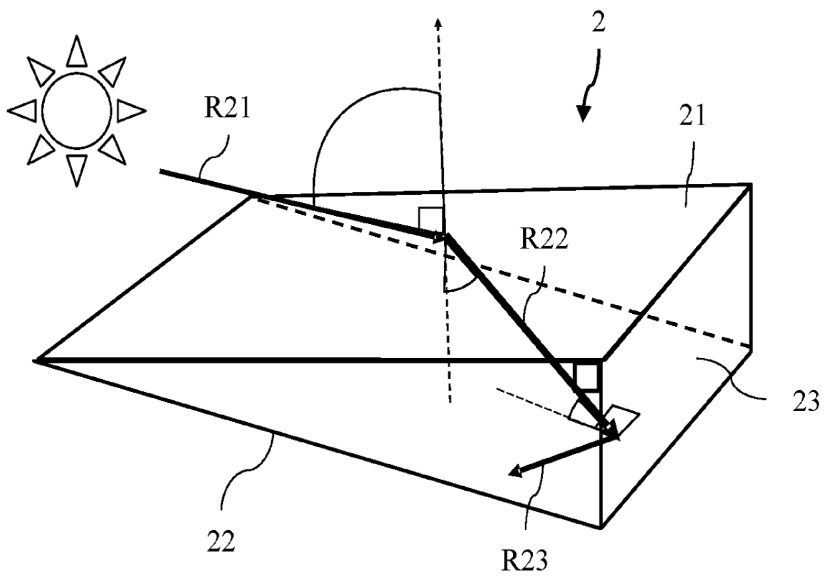

Fig. 3

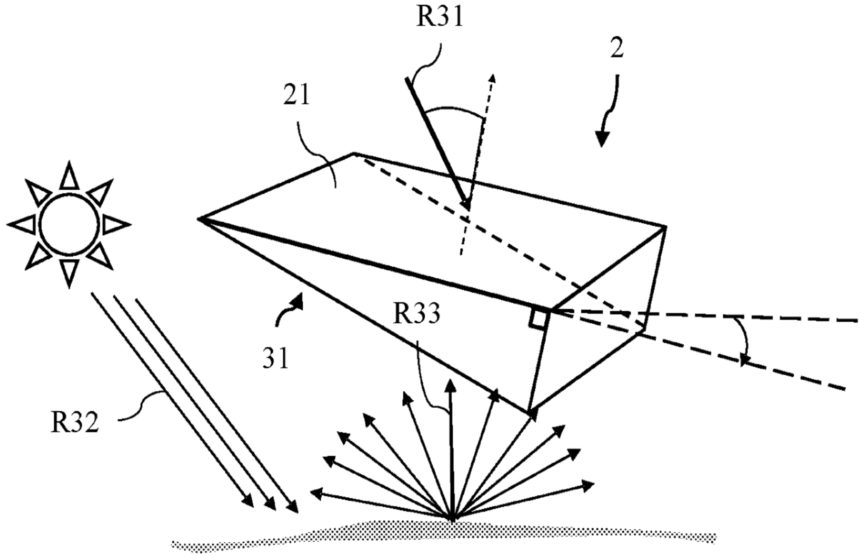

Fig. 4

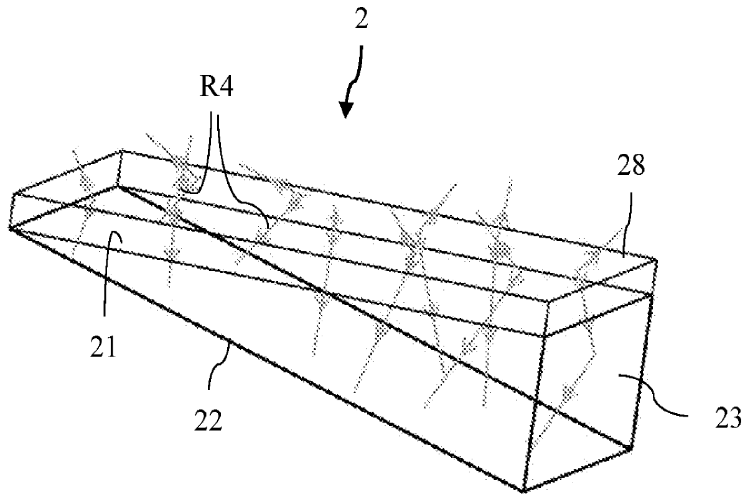

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2023/056165

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L31/054 H01L31/049 G02B19/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L H02S

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 10 2011 101029 A1 (SCHMIDT RAINER [DE]) 15 November 2012 (2012-11-15) paragraph [0015] -----	1-16
A	US 2010/269885 A1 (BENITEZ PABLO [ES] ET AL) 28 October 2010 (2010-10-28) paragraph [0014] paragraph [0061] paragraph [0066] paragraph [0080] - paragraph [0083] paragraph [0086] paragraph [0099] paragraph [0103] Facsimile page 4 Facsimile page 7 -----	1-16

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 August 2023	05/09/2023

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Chao, Oscar

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IT 2018 0000 7921 A1 (PARRETTA ANTONIO [IT]) 8 February 2020 (2020-02-08) Facsimile page 20 paragraph [0007] - paragraph [0008] -----	1-16
A	EP 2 534 701 B1 (FRAUNHOFER GES FORSCHUNG [DE]) 21 November 2018 (2018-11-21) paragraph [0009] paragraph [0025] paragraph [0054] -----	1-16

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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IT 201800007921	A1	08-02-2020	----------		
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			EP 2534701	A2	19-12-2012
			WO 2011098212	A2	18-08-2011