OPTIMUM SOLAR CONVERSION CELL CONFIGURATIONS

Methods for maximizing a fraction of light energy absorbed in each of three classes of light concentrators (rectangular parallelepipeds, paraboloids and prisms) by choice of incident angle of radiation and of one or more geometrical or physical parameters (absorber thickness, paraboloid dimensions, location of paraboloid focus, prism angles, concentrator material, cladding, prism angles, etc.). Alternatively, the light energy absorbed plus the light energy that escapes through non-total internal reflection within the light concentrator can be minimized.

22 Claims, 7 Drawing Sheets
FIG. 1
FIG. 2
FIG. 3

\[ y = \frac{x^2}{2k} \]

\[ (x = 0, \ y = \frac{k}{2}) \]

[Diagram showing geometric relationships and labels such as P1, M1, P2, M2, LB0, LB1, LB2, and angles.]
FIG. 4

\( x = 0, y = \frac{k}{2} \)

\( \theta_2, \theta_3 \)

\( 2d \)
OPTIMUM SOLAR CONVERSION CELL CONFIGURATIONS

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Public Law 96-517 (35 U.S.C. §202) in which the contractor elected not to retain title.

FIELD OF THE INVENTION

This invention relates to conversion of solar energy to other useful forms of energy, using optimized solar concentration and conversion cells.

BACKGROUND OF THE INVENTION

Polymeric and inorganic semiconductors offer relatively high quantum efficiencies, as high as 80 percent in the near-infrared and ultraviolet regions, and are much less expensive to fabricate than non-amorphous silicon wafers. An optical fiber and cladding can be designed and fabricated to confine light for transport within ultraviolet and near-IR media, using evanescent waves, and to transmit visible wavelength light for direct lighting. By using polymeric and less expensive and easily processable materials for fabrication, and by designing for optimum solar energy absorption for different solar concentrator configurations, the cost effectiveness of a solar energy conversion system can be increased substantially.

What is needed is one or more solar energy cell conversion configurations that are optimized with respect to choices of one, two or more important parameters, such as light incidence angle, geometric parameters of the conversion material, and choice(s) of conversion materials. Preferably, the materials should have reduced cost, relative to the costs of conventional systems, and the optimal configurations should be straightforward to implement. In addition to molding and casting processes, three dimensional additive manufacturing techniques can be used to implement the desired configurations.

SUMMARY OF THE INVENTION

These needs are met by the invention, which provides several solar conversion cells (SCCs) that are individually optimized to provide maximum energy absorption EA in a selected wavelength region, by appropriate choices of light incidence angle, one or more geometric parameters of the concentrator and/or choice(s) of conversion materials.

In a first embodiment, a broad or narrow light beam with an incidence angle 01 is received and internally reflected many times within a rectangular parallelepiped of thickness h of solar conversion material. EA can be optimized with respect to the incidence angle 01, the thickness h, a reflection coating of the initial light-receiving surface, and the parallelepipeded material refractive index ratio n2/n1. The second reflecting surface of the parallelepiped has substantially constant internal reflection (not necessarily 100 percent) for the incidence angle and wavelength region chosen.

In a second embodiment, a broad light beam is received by a truncated paraboloid surface, propagating parallel to the paraboloid axis, and the light is absorbed by a sphere or cylinder (solar concentrator) of solar conversion material of radius d whose center is coincident with the paraboloid focus. The energy absorption EA is optimized with respect to the location of the focus and the concentrator diameter 2d.

DESCRIPTION OF THE INVENTION

A light beam, emitted from a solar energy source such as the Sun, will pass through the Earth's atmosphere at different angular orientations, depending upon the time of day or night in a diurnal cycle and upon the location on the Earth's surface relative to the source of the incident light beam (e.g., the Sun). At high noon on the Equator (incidence angle 0=0° at edge of atmosphere) in mid-Summer or mid-Winter, the light beam will pass through one "air mass" (AM=1.0), measured by a line integral of the local air density, integrated along the path of the light beam. As the incidence angle 0 increases toward 90° at the horizon, the number of equivalent air masses AM increases monotonically.

FIG. 1 schematically illustrates effects of passage of solar radiation having different wavelengths through an air mass adjacent to the Earth's surface.

FIGS. 2-5 illustrate optimum energy absorption configurations for three representative types of solar concentrators: a rectangular parallelepiped (FIG. 2); a paraboloid (FIGS. 3 and 4); and a prism (FIG. 5).

FIGS. 6 and 7 illustrate a light collector mechanism that accepts and aligns light beams from a variety of directions.
µm–1 mm), with a first surface S1 that receives an incident light beam LBO (with a narrow wavelength band, centered at λ=λ0), propagating in a first material M1, having a refractive index n1 at an initial incidence angle θ1. The incident light beam is refracted into the SCC at a first surface S1 at a refraction angle θ2. A fraction, t(θ1) of the incident light beam is transmitted into the SCC with refraction angle θ2, propagates at an incidence angle θ2 relative to a second parallel surface S2, is internally reflected at the incidence angle θ2 at the second surface S2, propagates at incidence angle θ2 toward the surface S1, is reflected at the first surface S1 at incidence angle θ2, and repeats the reflection cycle (S1→S2→S1) an unlimited number of times (assuming the length of the SCC is very large or is infinite relative to a light beam cycle length 2θ=secθ2). The angles θ1 and θ2 for unpolarized light are related by Snell’s law,

\[
\begin{align*}
\sin θ1 &= n2 \sin θ2, \\
\cos θ1 &= 1 - (n2/n1)^2, \\
\sin θ1 &= \cos θ2.
\end{align*}
\]

(1), with appropriate modifications where polarized incident light is used. Light received from the sun is largely unpolarized, and the incident light received here is assumed to be unpolarized.

The transmission coefficient t(θ1) at the first surface S1 and the internal reflection coefficient r2(θ2) at the first surface S1 or the second surface S2 may depend upon wavelength λ(λ=λ0) and upon θ1 and θ2, and will behave according to the Fresnel reflection-transmission relations set forth in the following. A portion of the propagating light beam is absorbed with absorption coefficient α(λ) per unit length propagated within the SCC material. A fraction |β| (assumed–1 here) may be converted by the SCC material into electromagnetic energy with a higher wavelength (e.g., near-infrared, λ=λ1 ~ 0.8–2.0 µm). This converted wavelength light ("CWL") may be emitted preferentially in a transverse, longitudinal or other direction, for example at an angle y relative to the local direction of the path of the arriving light beam in the SCC material. The SCC has a small thickness h (e.g., 1 µm or a fraction thereof), measured in a direction perpendicular to a plane in which the light beam propagates (plane of the paper in FIG. 2).

The incident light beam enters the SCC at the first surface S1 with a transmission coefficient t(θ1) (also dependent upon wavelength λ). In a first reflection cycle (S1→S2→S1), this light beam propagates from the first surface S1 to the second parallel surface S2 at the angle θ2, is reflected at S2 with reflection coefficient r2(θ2), returns to S1 at the angle θ2, and is reflected at S1 at the angle θ2 as shown with reflection coefficient r2(θ2). For a first path segment (S1→S2): (1) the fraction of initial energy absorbed by or deposited within the SCC material M2 for a single path segment is t(θ1)e−αh, where e=exp[−αh secθ2]; (2) the fraction of energy transmitted (lost) through the surface S2 is t(θ1)(1−r2(θ2))e; and the fraction that is reflected at the surface S2 and propagates toward the surface S1 is t(θ1)e−r2(θ2). For a second segment (S2→S1): (1) the fraction of initial energy absorbed by the SCC material is t(θ1)(1−e−r2(θ2)); (2) the fraction transmitted (lost) through the surface S1 is t(θ1)(1−r2(θ2))e; and (3) the fraction that is reflected at the surface S1 and propagates toward the surface S2 is t(θ1)e−r2(θ2)². FIG. 2 also indicates (i) the fractions of energy absorbed along each path segment, S1→S2 or S2→S1, (ii) the fraction of energy that approaches each surface, S1 or S2, and (iii) the fraction of energy present after the beam is reflected at each surface, S1 or S2. For an infinite number of beam reflections at each of the surfaces, S1 and S2, the fraction of energy deposited within the SCC is

\[
t(θ1,θ2) = \frac{e^{-θ2}}{1 - (r2(θ2)e)} = \frac{e^{-θ2}}{1 - (r2(θ2)e)}.
\]

(4)

Because the incidence angle θ2 is constant for each cycle, the surfaces S1 and S2 can be coated with a thin film interference coating that approximately maximizes the reflection coefficient r2 or the coefficient (r2 e) for a given choice of the incidence angle θ2. This improvement can be incorporated in the SCC and in the reflection value used for r2 or for (r2 e). Determination of an optimal anti-reflection coating for a given incidence angle θ2 is discussed by H. A. MacLeod, Thin Film Optical Filters, Institute of Physics Publishing, 2001.

For a fixed SCC material M2, fixed thickness h, and fixed wavelength range, the total fraction F1 is maximized by determining an incidence angle θ2, satisfying Eq. (1), for which

\[
θ1(θ1, θ2) = θ1(θ1, θ2) = \frac{1}{2} \frac{π}{α}.
\]

(5)

\[
θ1(θ1, θ2) = θ1(θ1, θ2) = \frac{1}{2} \frac{π}{α}.
\]

(6)

For a fixed incidence angle θ2 and fixed wavelength range, the total fraction t1E1 is maximized with respect to thickness h by determining an SCC material thickness h for which

\[
\frac{∂θ1(E1)}{∂h} = 0;
\]

(9a)

or equivalently,

\[
\frac{∂θ1(E1)}{∂h} = 0;
\]

(9b)

Equation (11b) is satisfied where

\[
θ1→θ2 = 0;
\]

(9c)

which requires that θ2=1 (unrealistic). A more realistic optimization is to require that energy absorption per unit volume, proportional to (t1E1)/h, be maximized. This requirement is equivalent to

\[
\frac{∂θ1(E1)}{∂h} = 0;
\]

(10)

which represents optimization of energy absorbed per unit SCC thickness. The fraction F1 will increase monotonically with increasing attenuation coefficient α, but α is not a parameter that is controllable by the user.

Paraboloid.

FIG. 3 illustrates a second configuration of a solar cell energy concentrator, a two dimensional or three-dimensional paraboloid, defined by y=–x²/2k(1–D(x²)k), having a thickness Δh1 (e.g., ~1 µm), with a parabolic-shaped inner surface P1. An initial light beam LBO, moving parallel to a parabola central axis at a distance x from the y-axis (d(x²)k), and with a narrow wavelength band, centered at λ=λ0, is received at an
initial incidence angle \( \theta_1 = \theta_1(x) \) relative to a local portion of the inner surface \( P_1 \) (depending upon \( x \)), and is reflected as a first light beam portion \( L_{B1} \) toward the parabola focus \( F \), which has coordinates \((x=0, y=k/2)\). This reflected first light beam \( L_{B1} \) is received by and transmitted at normal incidence into a cylinder-shaped or sphere-shaped SCC of diameter \( 2d \), having a small thickness \( \Delta h_2 \) (e.g., a fraction of 1 mm) measured in a direction perpendicular to the plane of light beam propagation (plane of the paper in FIG. 3). As in the configuration of FIG. 2, a portion or all of the propagating light beam is absorbed by the SCC material. Within the volume enclosed by the parabolic surface \( P_1 \) and external to the SCC concentrator, the material is \( M_1 \) (which may be a partial or full vacuum or air with a selected density), and the SCC is comprised of an energy absorbing material \( M_2 \) with absorption coefficient \( \alpha(\lambda) \) per unit path length in the material \( M_2 \) (analogous to Eq. (2) for the rectangular parallelepiped material in the first configuration).

The first light beam intersects the parabola inner surface at an angle given by

\[
\cos \theta_1 = \frac{x}{\Delta h_2},
\]

relative to the \( x \)-axis and is reflected with a reflection coefficient \( r_1(\theta_1) \), which may depend upon the refractive indices, \( n_1 \) and \( n_2 \), and upon a surface coating for the surface \( P_1 \). This light beam is reflected by the surface \( P_1 \) at an angle \( 2\theta_1 \), intersects the SCC surface \( P_2 \) at normal incidence, and passes through the parabola focus \((x=0, y=k/2)\).

The surface \( P_2 \) of the SCC defines a cylinder or sphere of SCC material, having a diameter of length \( 2d \), an absorption coefficient of \( \alpha(\lambda) \) per unit path length \( \lambda \) in the interior of the paraboloid for the wavelength \( \lambda_0 \), and an associated absorption \( \alpha(d) \) for a light beam that passes along a diameter of the circular surface \( P_2 \). Preferably, \( 2ad \gg 1 \). The reflection coefficient \( r_1 \) associated with reflection at normal incidence from the first light beam from the inner surface \( P_1 \) is determined as

\[
r_1(\theta_2=0) = (n_2/n_1)(n_2+n_1)/2,
\]

where \( n_1 \) and \( n_2 \) are the (wavelength-dependent refractive indices of the materials, \( M_1 \) and \( M_2 \), respectively, indicated in FIG. 3. Optionally, it may be assumed that the material \( M_1 \) is substantially a vacuum so that \( n_1=1 \). The reflection coefficients \( r_1(\theta_1) \) and \( r_2(\theta_2) \) are determined using the Fresnel relations in Eqs. (5) and (6). The reflection coefficients \( r_1 \) and \( r_2 \) can be modified, for a given wavelength \( \lambda_0 \), by providing a reflective or anti-reflective coating on the corresponding reflecting surface, \( P_1 \) or \( P_2 \).

A second light beam portion \( L_{B2} \) moves parallel to the parabola axis, is displaced from the parabola axis by a distance \( x \) (\( -d \leq x \leq d \)), and is not intercepted by or reflected by the parabola inner surface \( P_1 \). This second light beam \( L_{B2} \) encounters the circular body at an incidence angle

\[
3 = \sin^{-1}(\alpha/d),
\]

which is generally non-perpendicular, as illustrated in FIG. 4, which illustrates \( L_{B1} \) and \( L_{B2} \) relative to the SCC. The corresponding reflection angle \( \theta_2 \) within the SCC (across surface \( P_2 \)) is determined from Snell’s law

\[
n_1 \sin \theta_2 = n_2 \sin \theta_3,
\]

for the \( M_1/M_2 \) interface. The path length \( 2d \) within the SCC for the refracted portion of the second component of the light beam \( L_{B2} \) is

\[
2d \cos \theta_3,
\]

and the attenuated fraction of the refracted component of the second light beam \( L_{B2} \) is

\[
3 = \sin^{-1}(\cos \theta_3/d).
\]
internally reflected without end from the three prism surfaces, $S_1$, $S_2$ and $S_3$, as indicated in FIG. 5. The triangular prism is defined, in part, by the three prism angles, $\psi_1$, $\psi_2$ and $\psi_3$ (assumed to be fixed), which satisfy

$$\psi_1 + \psi_2 + \psi_3 = \pi.$$  

(22)

FIG. 5 also illustrates an ordered sequence of reflection angles, $0_1$, $0_2$, $0_3$, $0_4$, $0_5$, $0_6$, $0_7$, etc. of internal reflections from the prism surfaces. The incident light beam encounters the first prism surface $S_1$ at initial incident angle $0_0$ and is transmitted into the prism and refracted at an initial refraction angle $0_1$. The once-refracted light beam $L_{131}$ approaches the second prism surface $S_2$ at an incident angle $0_2$, where

$$0_1 \equiv \frac{\pi}{2}, \quad \sin(\psi_2 + \psi_3) = \cos(\psi_2 + \psi_3) = 0.$$  

(23-1)

$$0_2 = \pi - 0_1.$$  

(23-2)

The once-refracted, once-internally reflected light beam $L_{132}$ approaches the third prism surface $S_3$ at an incident angle $0_3$, where

$$0_3 = \frac{\pi}{2} - \psi_3 + \psi_2 \sin(\psi_2 + \psi_3) = \cos(\psi_2 + \psi_3) = 0.$$  

(24-1)

$$0_2 - 0_1, \quad \sin(\psi_3) = \cos(\psi_3) = 0.$$  

(24-2)

The twice-internally reflected light beam $L_{133}$ approaches the second prism surface $S_2$ at an incident angle $0_4$, where

$$0_4 \equiv \frac{\pi}{2} - \psi_3 - \psi_2 \sin(\psi_2 + \psi_3) = \cos(\psi_2 + \psi_3) = 0.$$  

(25-1)

$$0_4 - 0_1, \quad \sin(\psi_3) = \cos(\psi_3) = 0.$$  

(25-2)

The next three angles of reflection, illustrated in FIG. 5, are determined by the relations

$$0_5 = \psi_3 - \psi_2 \sin(\psi_2 + \psi_3) = \cos(\psi_2 + \psi_3) = 0,$$

$$0_6 = \psi_3 - \psi_2 \sin(\psi_2 + \psi_3) = \cos(\psi_2 + \psi_3) = 0,$$

$$0_7 = \frac{\pi}{2} - 0_0.$$  

(26)

(27)

(28)

From this point on, it appears that the sequence of reflection angles repeats for general prisms. A shorter pattern of reflection angles may also develop. The incidence angle $0_4$ in Eq. (25-2) is equal to the initial refracted angle $0_1$ if and only if

$$\Psi_1 = \frac{\pi}{2} + \psi_3 = 0.$$  

(29)

$$0_4 = 0_0.$$  

(30)

Equations (22) and (2-25) require that

$$\psi_2 = \pi/2,$$

$$\psi_3 = \pi/2.$$  

(31)

(32)

in order that the light beam execute cycles within the prism with a sequence of repeating incidence angle triples, $(0_1, 0_2, 0_3, 0_4, 0_5, 0_6, 0_7, \ldots)$, Note that the locations on the prism surfaces where the incident light beams are reflected will normally not repeat. However, the reflection angle triples $(0_1, 0_2, 0_3)$ do repeat and are therefore predictable and determinable from $0_1$, or from $0_2$ or from $0_3$. A surface coating can therefore be determined for each of the prism surfaces, based on the respective reflection angle $0_1$, $0_2$ or $0_3$ for that surface, that maximizes the reflection coefficient and minimizes transmission coefficient at an M1/M2 interface. The choice of prism angles, $\psi_1$, $\psi_2$ and $\psi_3$ in Eq. (32) may lead to some simplifications in the subsequent analysis. However, in order to keep the scope as general as possible, general prism angles, $\psi_1$, $\psi_2$ and $\psi_3$ will be assumed here, including but not limited to the special constraint set forth in Eq. (32).
The optical module 71 need not be a full half circle or a full hemisphere but should have a planar lower surface that is contiguous to a planar upper surface of the optical fiber 64. Providing an optical module 71 that is less than half a circle or less than half a hemisphere will effectively mask a portion of the light source (e.g., solar). This is acceptable if the mask, located at the horizon, has an angular value more than about 10°-20°.

Where an optical module parameters satisfy Eqs. (40)-(48), a remainder of the received solar light beam will be received at or close to a selected (optimum) incident angle. Variation of the actual incident angle from the optimum incident angle will vary with the angular difference θ4 at 80.

Ideally, the refractive indices n1 and n2 are the same (02-03), and are relatively high, and the materials are reasonably transparent for the wavelength λ0 of interest. Impure flint glass has a refractive index in a range n=1.52-1.92. Titanium dioxide, diamond and strontium titanate have refractive indices in a range n=2.41-2.49. Sapphire has a refractive index in a range 1.76-1.78. Most other materials of interest have refractive indices no higher than about 1.6.

What is claimed is:

1. A method for receipt and optimal concentration of light beam energy in a solar energy conversion cell, the method comprising:
   - providing a light energy conversion cell (LECC), having a rectangular parallelepiped shape, comprising first and second, parallel, planar, light-receiving and reflecting surfaces, S1 and S2, facing each other and spaced apart a distance h, and further comprising a material M2 of thickness k, positioned between the surfaces S1 and S2 and having an LECC refractive index n2(X) at a representative wavelength X of a solar radiation light beam; positioning the LECC to receive an incident solar radiation light beam, propagating in a first medium M1 having a refractive index n1(X), at an initial incidence angle θ1 at the first surface S1; and
   - allowing the first surface S1 to transmit and refract a portion of the received light beam, with a transmission coefficient, τ1=τ1(θ1), into the material M2 at a refraction angle θ2, and permitting the received light beam to propagate from the first surface S1 to the second surface S2 at an internal reflection angle equal to θ2, to be reflected at the surface S2 with a reflection coefficient, r2=r2(θ2), and to return toward the first surface S1 at the internal reflection angle θ2, where the internal reflection angle θ2 and the initial incidence angle θ1 satisfy a Snell’s law relation between the angles θ1 and θ2 for at least one of the first surface S1 and the second surface S2;
   - allowing the portion of the received solar radiation within the LECC to be reflected alternatingly at least two times from the surface S1 and from the surface S2; estimating a fractional attenuation coefficient, e=−(e(θ2)), of the refracted light beam in propagating once between the surface S1 and the surface S2; estimating a fraction u(θ1) E(θ1,θ2) of light beam energy absorbed by the M2 material; and

What is claimed is:

1. A method for receipt and optimal concentration of light beam energy in a solar energy conversion cell, the method comprising:
   - providing a light energy conversion cell (LECC), having a rectangular parallelepiped shape, comprising first and second, parallel, planar, light-receiving and reflecting surfaces, S1 and S2, facing each other and spaced apart a distance h, and further comprising a material M2 of thickness k, positioned between the surfaces S1 and S2 and having an LECC refractive index n2(X) at a representative wavelength X of a solar radiation light beam; positioning the LECC to receive an incident solar radiation light beam, propagating in a first medium M1 having a refractive index n1(X), at an initial incidence angle θ1 at the first surface S1; and
   - allowing the first surface S1 to transmit and refract a portion of the received light beam, with a transmission coefficient, τ1=τ1(θ1), into the material M2 at a refraction angle θ2, and permitting the received light beam to propagate from the first surface S1 to the second surface S2 at an internal reflection angle equal to θ2, to be reflected at the surface S2 with a reflection coefficient, r2=r2(θ2), and to return toward the first surface S1 at the internal reflection angle θ2, where the internal reflection angle θ2 and the initial incidence angle θ1 satisfy a Snell’s law relation between the angles θ1 and θ2 for at least one of the first surface S1 and the second surface S2;
   - allowing the portion of the received solar radiation within the LECC to be reflected alternatingly at least two times from the surface S1 and from the surface S2; estimating a fractional attenuation coefficient, e=−(e(θ2)), of the refracted light beam in propagating once between the surface S1 and the surface S2; estimating a fraction u(θ1) E(θ1,θ2) of light beam energy absorbed by the M2 material; and

Variation of the actual incident angle from the optimum incident angle will vary with the angular difference θ4 at 80.

Ideally, the refractive indices n1 and n2 are the same (02-03), and are relatively high, and the materials are reasonably transparent for the wavelength λ0 of interest. Impure flint glass has a refractive index in a range n=1.52-1.92. Titanium dioxide, diamond and strontium titanate have refractive indices in a range n=2.41-2.49. Sapphire has a refractive index in a range 1.76-1.78. Most other materials of interest have refractive indices no higher than about 1.6.

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1. A method for receipt and optimal concentration of light beam energy in a solar energy conversion cell, the method comprising:
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   - allowing the first surface S1 to transmit and refract a portion of the received light beam, with a transmission coefficient, τ1=τ1(θ1), into the material M2 at a refraction angle θ2, and permitting the received light beam to propagate from the first surface S1 to the second surface S2 at an internal reflection angle equal to θ2, to be reflected at the surface S2 with a reflection coefficient, r2=r2(θ2), and to return toward the first surface S1 at the internal reflection angle θ2, where the internal reflection angle θ2 and the initial incidence angle θ1 satisfy a Snell’s law relation between the angles θ1 and θ2 for at least one of the first surface S1 and the second surface S2;
selecting at least one of the angles \( \theta_1 \) and \( \theta_2 \) to provide an approximate maximum for the fraction \( F(\theta_2, h; \lambda) \) of light beam energy absorbed by the LECC.

2. The method of claim 1, further comprising estimating said fraction \( t(01) = \frac{\theta_1}{\theta_2} \) as

\[
\frac{t(01)E_0(01,02) - r_1(01)\epsilon(1-\epsilon+2(1-\epsilon_0,02,01))}{1-\epsilon}
\]

and estimating said fractional attenuation coefficient as

\[
e(\rho,\theta) = \exp\left[-\sqrt{\frac{\alpha(\lambda)}{\epsilon(\lambda,\theta)}} \rho \right]
\]

where \( \alpha(\lambda) \) is an absorption coefficient associated with propagation of the light beam energy within said material \( M_2 \), \( t(01) \) and \( r(02) \) are said light beam transmission coefficient and said light beam reflection coefficient, respectively, for said light beam energy received at said surface \( S_1 \), traveling within said second material \( M_2 \).

3. The method of claim 2, further comprising applying said Snell's law relation in a form \( n_1(\lambda) \sin \theta_1 = n_2(\lambda) \sin \theta_2 \).

4. The method of claim 3, wherein at least one of said angles, \( \theta_1 \) and \( \theta_2 \), is chosen to provide said approximate maximum of said fraction \( t(01) = \frac{\theta_1}{\theta_2} \) by a process comprising: selecting at least one of said angles, \( \theta_1 \) and \( \theta_2 \), to satisfy said Snell's law relation and to satisfy at least one of the relations \( r(01)E_0(01,02) \theta_1 - 0 \) or \( r(01)E_0(01,02) \theta_2 - 0 \), where \( \theta_1 \) and \( \theta_2 \) are related by said Snell's law relation.

5. The method of claim 1, further comprising choosing said material \( M_1 \) to be either a vacuum or air with a selected mass density or pressure.

6. The method of claim 1, further comprising choosing said material \( M_2 \) to comprise at least one inorganic material, drawn from a group consisting of bismuth oxides (\( \text{Bi}_2\text{O}_3 \)), bismuth iodides (\( \text{Bi}_2\text{I}_3 \)), lead iodide (\( \text{PbI}_2 \)), cadmium sulfide (\( \text{CdS} \)), cadmium selenide (\( \text{CdSe} \)) and cadmium telluride (\( \text{CdTe} \)), where \( a, b, c, d \) and \( e \) are positive numerical values.

7. The method of claim 1, further comprising choosing said material \( M_2 \) to comprise at least one polymer, drawn from a group consisting of poly(2-methoxy-5-(2'-ethylhexyloxy)-p-phenylenevinylene] (MEH-PPV), olefamine, polythiophene and derivatives thereof, and poly[4,8-bis-substituted-benzo [1,2-b:4,5-b']diopheno-2,6-diyl-alt-4-substituted-thieno[3,4-b][thiophene-2,6-diyl]] (PBBTTTF-CF).

8. The method of claim 1, further comprising receiving said incident light beam at a light energy collection mechanism that redirects said incident light beam, received at said incident angle \( \theta_1 \), to a selected and modified incident angle \( \theta_1(\text{sel}) \) and delivers the redirected incident light beam to said first surface \( S_1 \).

9. A method for receipt and optimal concentration of light beam energy in a solar energy conversion cell, the method comprising:

- providing a light energy conversion cell (LECC), comprising (i) a paraboloid shaped surface \( P_1 \), expressed in Cartesian coordinates \( (x,y) \) in a form \( y = x^2/k \), with \( k \) for a selected positive distance \( D \), and with a paraboloid focus located approximately at a position with coordinates \( (x=0,y=k/2) \) and having a paraboloid longitudinal axis that passes through the focus, where an inner surface of the paraboloid reflects a light beam incident on the paraboloid inner surface, and (ii) a light beam concentrator, shaped as a circle or cylinder with a center located at the paraboloid focus, where the light concentrator has a diameter \( 2d \) and comprises a light-receiving material \( M_2 \) that receives and refracts into an interior of the cylinder a light beam, having a representative wavelength \( \lambda \) incident on a circle or cylinder surface of the material \( M_2 \), and part or all of said light beam energy is deposited in the material, where the light beam propagates a path distance \( \Delta s \) in the material \( M_2 \) with a fractional attenuation coefficient \( \epsilon(\Delta s) \), where a material \( M_1 \), positioned between the paraboloid surface and the circle or cylinder, permits propagation of the light beam; positioning the LECC to receive a first portion of the light beam propagating in the material \( M_1 \) at a selected incidence angle \( \theta_1 \) at the paraboloidal inner surface \( P_1 \) and to reflect the first portion toward the parabola focus; positioning the paraboloid surface and the circle or cylinder to initially receive a second portion of the light from a beam direction oriented approximately parallel to the paraboloid longitudinal axis and propagating within a distance \( d \) of the paraboloid longitudinal axis, where \( \theta = \pi d D \).

10. The method of claim 9, further comprising applying said Snell’s law relation in a form \( n_1(\lambda) \sin \theta_1 = n_2(\lambda) \sin \theta_2 \).

11. The method of claim 9, further comprising estimating said fractional attenuation coefficient \( \epsilon(\lambda,\theta) \) as

\[
e(\lambda,\theta) = \exp\left[-\sqrt{\frac{\alpha(\lambda)}{\epsilon(\lambda,\theta)}} \rho \right]
\]

where \( \alpha(\lambda) \) is a light beam absorption coefficient, which may depend upon said wavelength \( \lambda \), along a path of said length \( \Delta s \) in said material \( M_2 \).

12. The method of claim 11, further comprising estimating said fraction \( F(k,d,D,\lambda) \) as

\[
F(k,d,D,\lambda) = \frac{E_1(k,d,D,\lambda)}{E_2(\theta_1,D,\lambda)}
\]

where \( \alpha(\lambda) \) is said light beam absorption coefficient associated with propagation of said light beam within said material \( M_2 \), \( r(\theta_1,D,\lambda) \) is a light beam reflection coefficient for said light beam energy received at said parabola inner surface and, \( \theta_2 = \theta(02) \) is a light beam transmission coefficient for said light beam energy received at said circle or cylinder surface.

13. The method of claim 9, further comprising:

- selecting at least one of said values \( k, D \) and \( d \) in order to approximately maximize said fraction \( \frac{E_1(k,d,D,\lambda)}{E_2(\theta_1,D,\lambda)} \).

14. The method of claim 13, wherein at least one of said qualities \( k, D \) and \( d \) is chosen to provide said approximate maximum of said fraction \( F = \frac{E_1(k,d,D,\lambda)}{E_2(\theta_1,D,\lambda)} \) by a process comprising: selecting at least one of said quantities \( k, d \) and \( D \) to approximately maximize the fraction \( E_1(k,d,D,\lambda)/E_2(\theta_1,D,\lambda) \) of said light beam energy delivered to and absorbed in said light beam concentrator.

15. The method of claim 9, further comprising choosing said material \( M_1 \) to be either a vacuum or air with a selected mass density or pressure.

16. The method of claim 9, further comprising choosing said material \( M_2 \) to comprise at least one inorganic material, drawn from a group consisting of poly[2-methoxy-5-(2'-ethylhexyloxy)-p-phenylenevinylene] (MEH-PPV), olefamine, polythiophene and derivatives thereof, and poly[4,8-bis-substituted-benzo [1,2-b:4,5-b']diopheno-2,6-diyl-alt-4-substituted-thieno[3,4-b][thiophene-2,6-diyl]] (PBBTTTF-CF).

17. The method of claim 9, further comprising choosing said material \( M_2 \) to comprise at least one polymer, drawn from a group consisting of poly[2-methoxy-5-(2'-ethylhexyloxy)-p-phenylenevinylene] (MEH-PPV), olefamine, polythiophene and derivatives thereof, and poly[4,8-bis-substituted-benzo [1,2-b:4,5-b']diopheno-2,6-diyl-alt-4-substituted-thieno[3,4-b][thiophene-2,6-diyl]] (PBBTTTF-CF).
13
loxy)-p-phenylenevinylene] (MEH-PPV), oleamide, poly-
thiophene and derivatives, and poly[4,8-bis-substituted-
benzo[1,2-b:4,5-b']dithiophene-2,6-diyl-alt-4-substituted-
thieno[3,4-b]thiophene-2,6-diyl] (PBBTTT-CF).

18. The method of claim 9, further comprising receiving
said incident light beam at a light energy collection mecha-
nism that redirects said incident light beam, received at said
incident angle 01, to a selected and modified incident angle
01(sel) and delivers the redirected incident light beam to said
parabola surface P1.

19. A method for receipt and optimal concentration of light
beam energy in a solar energy conversion cell, the method
comprising:

- providing a light energy conversion cell (LECC) as a tri-
angular prism, comprising first, second and third light
reflecting surfaces, where the first and second prism
surfaces intersect at a first prism angle θ1, the second
and third prism surfaces intersect at a second prism angle
θ2, and the third and first prism surfaces intersect at a
prism angle θ3, with θ1 + θ2 + θ3 = π, and the prism com-
prises a prism material M2 that supports propagation of
a light beam therein, and where the material M2 has a
refractive index n2(λ) for a light beam with a repre-
sentative wavelength λ;

- positioning the LECC to receive a solar radiation light
beam, having the representative wavelength λ, and propa-
gating in an ambient medium M1 that has a refrac-
tive index n1(λ), at an initial incidence angle θ0, at the
first prism surface, and permitting a portion of the light
beam to be transmitted into and refracted within the
material M2 with a refraction angle θ1, where the angles
θ0 and θ1 are related by a Snell’s law relation;

- allowing the refracted light beam to propagate within
the material M2 to be alternatively reflected from the
second surface, the third surface and the first surface at
least two times within the material M2;

- estimating a fraction t1(θ0) EA(θ0, θ1, θ2; θ3; Δs) of
the light beam energy deposited in the material M2 for at
least two cycles of the light beam, each cycle including
at least one reflection from the second surface, the third
surface and the first surface, where a cycle of the light
beam has a representative path length Δs for a propagat-
ing light beam that is consecutively reflected from the
second surface, from the third surface and from the first
surface, or from the third surface, the second surface and
the first surface, where t1(θ0) is a transmission coeffi-
cient for the incident light beam at the first surface for an
incidence angle θ0;

- selecting at least one of the angles θ0 and θ1 to provide an
approximate maximum for the fraction t1(θ0) EA(θ0,
θ1,θ2;θ3;Δs) of the light beam energy deposited in
the material M2.

20. The method of claim 19, further comprising estimating
said fraction F(θ1, θ2; λ) as

\[ F(\theta_1, \theta_2; \lambda) = \frac{t_1(\theta_0) E(\theta_0, \theta_1, \theta_2, \theta_3; \Delta s) r_1(\theta_0, \theta_1, \theta_2, \theta_3; \Delta s; \lambda)}{k(1 - e^{-\alpha(\lambda) \Delta s})} \]

and estimating a fractional attenuation coefficient as

\[ e(\Delta s) = e^{-\alpha(\lambda) \Delta s} \]

where α(λ) is an absorption coefficient associated with
propagation of the light beam energy within said material M2,
and t1(θ0) and r2(01, λ) are said light beam transmission
coefficient and said light beam internal reflection coefficient,
respectively, for said light beam energy received at said first
surface.

21. The method of claim 19, further comprising applying
said Snell’s law relation in a form n1(λ) sin θ1 = n2(λ) sin θ2
for said refraction of said incident solar radiation light beam
at said first prism surface.

22. The method of claim 19, further comprising receiving
said incident light beam at a light energy collection mecha-
nism that redirects said incident light beam, received at said
incident angle 01, to a selected and modified incident angle
01(sel) and delivers the redirected incident light beam to said
first surface.

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