Title: BAND PASS FILTER FOR SOLAR RADIATION

Abstract: According to the present invention there is provided a solar radiation band pass filter system for producing electrical current from concentrated solar radiation. The solar radiation is in the wavelength range W ranging from a wavelengths v1*v2. The range W comprises at least three sub-ranges: W1 including v1, W3 including v2, and W2 separating W1 and W3, and not including v1 and v2. The system comprises a beam splitter adapted for splitting the concentrated solar radiation into a first beam carrying radiation of sub-range W2 and directed in a first direction, and a second beam carrying radiation of sub-range W1 and W3 directed in a second direction. The system further comprises a first photovoltaic receiver adapted for producing electrical current from the first beam, and a second photovoltaic receiver adapted to produce electrical current from the second beam.
FIELD OF THE INVENTION

This invention relates to solar radiation utilization systems, in particular systems utilizing photovoltaic cells.

BACKGROUND OF THE INVENTION

Solar concentrators are used to concentrate sunlight/solar radiation for various applications such as solar thermal, concentrated photovoltaic or hybrid lighting, and usually employ a primary concentrator in the form of a reflective type i.e. mirror or a diffractive type such as a fresnel lens adapted for concentrating the solar radiation into a predetermined target.

Solar utilization systems are also known to comprise secondary concentrators, often used for any one of several reasons:

a. increasing the concentration level obtained by the primary concentrator;
b. redirecting the concentrated beam into the receiver;
c. homogenizing the beam on the receiver;
d. offset for tracking and misalignment errors;

It is known in the art the use of the above solar concentrators as well as beam splitters adapted to split solar radiation into different wavelength and using different photovoltaic cells for each wavelength range. Thus, for example, WO06030433 to the applicant discloses one such system.

"Band gap engineering in high efficiency multijunction concentrator cells" to Spectrolab discloses the use of photovoltaic cells comprising several layer adapted for producing electrical current from different wavelength ranges. Similar subject matter is disclosed in "Ultrahigh efficiency microconcentrators PV" to CalTech and the Aonex corporation.
SUMMARY OF THE INVENTION

According to the present invention there is provided a solar radiation band pass filter system for producing electrical current from concentrated solar radiation in the wavelength range W ranging from a wavelengths \( v_1 + v_2 \), comprising at least three sub-ranges \( W_1 \) including \( v_1 \), \( W_3 \) including \( v_2 \), and \( W_2 \) separating \( W_1 \) and \( W_3 \), and not including \( v_1 \) and \( v_2 \), said system comprising a beam splitter adapted for splitting said concentrated solar radiation into a first beam carrying radiation of sub-range \( W_2 \) and directed in a first direction, and a second beam carrying radiation of sub-range \( W_1 \) and \( W_3 \) directed in a second direction, said system further comprising a first photovoltaic receiver adapted for producing electrical current from said first beam, and a second photovoltaic receiver adapted to produce electrical current from said second beam.

In particular, the wavelength range \( W \) may be 300–1800nm, and the sub-ranges may be, for example, 300–800nm, 800–1100nm and 1100–1800nm for \( W_1 \), \( W_2 \) and \( W_3 \) respectively.

The system may be adapted to constitute a part of a system for solar utilization comprising a primary concentrator adapted for receiving solar radiation incident thereon and concentrating it towards a second concentrator in the form of a beam splitter. The second concentrator may be associated with said first photovoltaic receiver and adapted for further concentration of said solar radiation into a second receiver. Said first receiver may comprise therein a first photovoltaic cell and said second receiver may comprise therein a second photovoltaic cell.

The system may be of a cassegrainian design, wherein said first beam splitter is covered by a dichroic coating, allowing radiation of the first beam with second sub-range \( W_2 \) to penetrate said coating and reach said first receiver, while deflecting said second beam of sub-ranges \( W_1 \) and \( W_3 \) together towards said second photovoltaic cell.

The first photovoltaic receiver may be adapted for producing current from said first beam, and may comprise a first photovoltaic cell made, for example, of silicon. Silicon material has inherent characteristics including sensitivity to the specific wavelength range of \( W_2 \) as well as an atomic spacing \( A_1 \). Due to the fact that said first photovoltaic cell receives solar radiation of an essentially limited wavelength range (800–1100nm), the amount of heat to be removed from the first receiver is consequently limited, allowing the design of a heat sink for said receiver to be of dimensions minute enough so as not to obstruct solar radiation from said first concentrator. Silicon has a
band gap of 1.12ev and may thus be adapted to produce electrical current from solar radiation of up to 1100nm.

The second photovoltaic cell may comprise several layers, each of a different material, and having inherent characteristics adapted for producing electrical current from a predetermined wavelength range. Thus, the photovoltaic cell may be formed of a first material sensitive to said first sub-range W₁ and a second material sensitive to said thirds sub-range W₃. Furthermore, several materials may be used for each sub-range. For example, said photovoltaic cell may be of a triple junction type comprising a first layer of InGaP (Indium Gallium Phosphorus) which has a band gap of 1.8ev and is sensitive to wavelengths up to about 600nm, GaAs (Gallium Arsenide) which has a band gap of 1.4ev and is sensitive to wavelengths up to about 800nm, and Ge (Germanium) which has a band gap of 0.67ev and is sensitive to wavelengths of up to about 1800.

The materials used in the second photovoltaic cell may have a similar atomic spacing A₃≠A₁ allowing the production of said photovoltaic cell in conentional and cost efficient manner without the use of adhesives, i.e. crystal growing method resulting in a monolithic cell. Alternatively, the materials may be of various atomic spacing requiring the use of an adhesive to attach the layers to one another.

Each of the materials may be sensitive to solar radiation of a different wavelength. It is known in the art to use a beam splitter in order to deflect towards the second receiver solar radiation in the range of about 400÷1800nm, in which a photovoltaic cell as described above is positioned.

As common in most photovoltaic cells, the layers of the above triple junction photovoltaic cell needs to be current matched, i.e. adjusting the amount of current produced by all three materials to be the same.

It should be noted that the gap between the wavelength sensitivity of Germanium (1800nm, 0.67ev) and that of Gallium Arsenide (800nm, 1.4ev) is much greater than that of the gap between Gallium Arsenide (800nm, 1.4ev) and Indium Gallium Phosphorus (600nm, 1.8ev). Thus the germanium receives an excess amount of solar radiation rendered misused, thereby complicating current matching and reducing the efficiency of the entire photovoltaic cell. This is a common problem in the field.

It would thus be desirable to have a material which has a band gap between 1.0÷1.2ev and is sensitive to a wavelength of about 800÷1100nm. Silicon is known to
have characteristics similar to those described above, i.e. about 1100nm, 1.12 ev. Unfortunately, the atomic spacing of Silicon is different from that of the above three materials, preventing the production of a four-layer monolithic photovoltaic cell to be positioned in the second receiver, the production being done in a conventional and cost efficient manner.

However, according to the present invention, the solar radiation reflected off the beam splitter towards the second receiver may be of two wavelength sub-ranges $W_1$ 400+800nm and $W_2$ 1100+1800nm, while solar radiation of wavelength sub-range $W_2$ 800+1100nm may be allowed to pass towards the first photovoltaic cell. This yields that the amount of solar radiation incident on the Germanium layer is now of lesser amount compared to conventional configurations.

Thus, instead of creating a four-layer monolithic photovoltaic cell, two cells are used. The first photovoltaic cell may be made of a monolithic piece of silicon, adapted to produce electrical current from the solar radiation directed thereto in the specific wavelength range of 800+1100nm. The second photovoltaic cell may be a standard cell as described above, i.e. InGaP+GaAs+Ge but avoiding the excess solar radiation reflected on the Germanium since it now receives just wavelengths of 1100+1800.

According to the above configuration, the entire wavelength range from 400+1800 is optimally utilized, and allows a convenient current matching between all three layers of the second photovoltaic cell and the current of the first photovoltaic cell.

It should be noted that the currents produced by the silicon and the triple junction photovoltaic cell need to be current matched for optimal operation of the system. Current matching may be achieved, inter alia, by adding Al (Aluminum) to the layers, thus raising the band gap of each layer, e.g. AlGaInP 2.0ev, AlGaAs 1.5ev and Ge 0.7ev, thus allowing the first photovoltaic cell (Silicon) to produce same current and produce maximum voltage possible for maximum power output of this 4 band gaps configuration.

According to the present invention, a combination of the above materials may produce a theoretical efficiency of about 58%. It would be appreciated that a number of variations and optimizations may be achieved by using a variety of materials with different inherent characteristics.

It should also be appreciated that the solar radiation directed towards said second photovoltaic cell may be further split into its two sub-range $W_1$ and $W_3$, each
being directed towards a photovoltaic cell specifically designed to produce an electrical current therefrom.

A significant advantage of the system according to the present invention is the ability to efficiently utilize a middle portion of the solar radiation wavelength range $W_2$ in a first photovoltaic cell separate from said second photovoltaic cell, having an atomic spacing different from the materials forming the second cell, and each of the cells being monolithic.

According to another aspect of the present invention there is provided a beam splitter to be used in a solar radiation band pass filter system for producing electrical current from concentrated solar radiation in the wavelength range $W$ ranging from a wavelengths $v_1+v_2$, comprising at least three sub-ranges $W_1$ including $v_1$, $W_3$ including $v_2$, and $W_2$ separating $W_1$ and $W_3$, and not including $v_1$ and $v_2$, said beam splitter being adapted for splitting said concentrated solar radiation into a first beam carrying radiation of sub-range $W_2$ and directed in a first direction, and a second beam carrying radiation of sub-range $W_1$ and $W_3$ directed in a second direction.

**BRIEF DESCRIPTION OF THE DRAWINGS**

In order to understand the invention and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

- **Fig. 1A** is a schematic view of a solar utilization system comprising the band pass filter system according to the present invention;

- **Fig. 1B** is a schematic diagram of the solar radiation wavelength range after passing the band pass filter according to the present invention;

- **Fig. 2** is a schematic view of the solar radiation spectrum and wavelength sub-ranges according to the prior art;

- **Fig. 3A** is a schematic view of the solar radiation spectrum and wavelength sub-ranges used by a receiver according an embodiment to the present invention;

- **Fig. 3B** is a schematic view of the solar radiation spectrum and wavelength sub-ranges used by a receiver according an embodiment to the present invention;
DETAILED DESCRIPTION OF EMBODIMENTS

Referring to Fig. 1A, a solar utilization system generally designated 10 is shown comprising a primary reflective concentrator 20, a secondary reflective concentrator in the form of a beam splitter 30, a receiver with a photovoltaic cell 40, a second receiver with a photovoltaic cell 50, and a shielding cover 18 adapted to protect the system 10 from environmental damage such as dust, oxidation etc., as well as preventing losses of radiation. The primary concentrator 20 and the beam splitter 30 are located along a main optical axis thereof X-X.

The primary reflective concentrator 20 is in the form of a parabolic dish having a reflective surface \( R_p \) adapted to reflect incident light-beams \( LB \) to its focal point \( f_p \). The focal point \( f_p \) is located adjacent the secondary reflective concentrator, and behind reflective surface \( R_s \) thereof.

The beam splitter 30 is in the form of a conical collector 32 made of a transparent material, e.g. glass, having an input end which is a parabolic reflective surface \( R_s \). The reflective surface \( R_s \) is applied with a dichroic coating allowing solar radiation of a predetermined wavelength range \( W_2 \) of about 800–1100nm to penetrate the reflective surface \( R_s \) and enter into a collector 32. The collector 32 then directs the light-beams by inner reflection to a photovoltaic cell 40.

The remainder of light beams of wavelength sub-ranges \( W_1 \) 400–800nm, and \( W_3 \) 1100–1800nm are reflected by the reflective surface \( R_s \) to the focal point \( f_s \) of the secondary concentrator. The focal point \( f_s \) of the secondary reflective concentrator is located under the primary concentrator 20, and is associated with a second photovoltaic cell 50. The primary reflective concentrator 20 is formed with a hole in its middle 22 allowing light beams reflected off the secondary concentrator 20 to reach the second photovoltaic cell 50.

Splitting the solar radiation into wavelength ranges allows a more efficient use of photovoltaic cells, wherein each cell is specially designed to produce energy from a predetermined range of solar radiation. This in turn reduces the amount of radiation incident on each photovoltaic cell, consequently making it absorb less heat, reducing the risk of damage to the photovoltaic cells 40, 50.

Furthermore, due to the essentially narrow wavelength range received within the collector 32, the amount of heat which needs to be removed therefrom is essentially low, allowing the heat sink installed on the beam splitter 30 to be designed to have
dimension small enough so as not to obstruct solar radiation from the primary concentrator 20.

Turning to Fig. 2, a scheme of the solar radiation spectrum is shown along with voltage (ev) values for a standard triple junction photovoltaic cell comprising three layers made of InGaP, GaAs and Ge. In this case all the solar radiation in the wavelength range of 400–1800 is incident on the triple junction photovoltaic cell.

Reverting to Fig. 1A and with reference to Fig. 1B, in the present configuration, the solar radiation reflected off the beam splitter 30 towards the second receiver and photovoltaic cell 50 is of two wavelength sub-ranges \( W_1 \) 600–800nm and \( W_3 \) 1100–1800nm, while solar radiation of wavelength sub-range \( W_2 \) 800–1100nm is allowed to pass towards the first photovoltaic cell 40.

Thus, the first photovoltaic cell may be made of a monolithic piece of silicon, which has a band gap of 1.12ev and is thus adapted to produce electrical current from the solar radiation directed thereto in the specific wavelength range of 800–1100nm.

The second photovoltaic cell 50 may be a standard cell as described above, i.e. InGaP+GaAs+Ge but receiving less solar radiation thus avoiding the excess radiation on the Germanium since it now receives just wavelengths of 1100–1800.

Turning to Fig. 3B, the layers of the standard photovoltaic cell may be further improved by adding Aluminum to the layers, resulting in layers which are more sensitive to solar radiation, i.e. AlInGaP having a band gap of 2.0ev, AlGaAs with a band gap of 1.49ev and Ge with a band gap of 0.67ev. Such a configuration may produce an efficiency of about 57%.

Those skilled in the art to which this invention pertains will readily appreciate that numerous changes, variations, and modifications can be made without departing from the scope of the invention, *mutatis mutandis*. 
CLAIMS:

1. A solar radiation band pass filter system for producing electrical current from concentrated solar radiation in the wavelength range \( W \) ranging from a wavelengths \( v_1 + v_2 \), comprising at least three sub-ranges \( W_1 \) including \( v_1 \), \( W_3 \) including \( v_2 \), and \( W_2 \) separating \( W_1 \) and \( W_3 \), and not including \( v_1 \) and \( v_2 \), said system comprising a beam splitter adapted for splitting said concentrated solar radiation into a first beam carrying radiation of sub-range \( W_2 \) and directed in a first direction, and a second beam carrying radiation of sub-range \( W_1 \) and \( W_3 \) directed in a second direction, said system further comprising a first photovoltaic receiver adapted for producing electrical current from said first beam, and a second photovoltaic receiver adapted to produce electrical current from said second beam.

2. A system according to Claim 1, wherein the wavelength range \( W \) is 300\( \div \)1800nm.

3. A system according to Claim 2, wherein said wavelength ranges are about 300\( \div \)800nm, 800\( \div \)1100nm and 1100\( \div \)1800nm for \( W_1 \), \( W_2 \) and \( W_3 \) respectively.

4. A system according to Claim 1 adapted to constitute a part of a system for solar utilization comprising a primary concentrator adapted for receiving solar radiation incident thereon and concentrating it towards a second concentrator in the form of a beam splitter.

5. A system according to Claim 1, wherein said system is of cassegranian design and said beam splitter is covered with a dichroic coating adapted to split said solar radiation into said first beam and said second beam.

6. A system according to Claim 1, wherein each of said first receiver comprises a first photovoltaic cell and said second receiver comprises a second photovoltaic cell.

7. A system according to Claim 6, wherein said first photovoltaic cell is Silicon based.

8. A system according to Claim 7, wherein said first photovoltaic cell has a band gap of about 1.12ev and is sensitive to radiation of a wavelength range of up to about 1100nm.

9. A system according to Claim 6, wherein said second photovoltaic cell is a triple junction photovoltaic cell.

10. A system according to Claim 9, wherein said photovoltaic cell is monolithic.
11. A system according to Claim 9, wherein said triple junction cell is made of a first layer of InGaP, a second layer of GaAs and a third layer of Ge.

12. A system according to Claim 10, wherein said first, second and thirds layers have band gaps of 1.8ev, 1.4ev and 0.67ev respectively and are sensitive to the following wavelength ranges of up to about 600, 800 and 1800, respectively.

13. A system according to Claim 9, wherein said triple junction cell is made of a first layer of AlInGaP, a second layer of AlGaAs and a third layer of Ge.

14. A system according to Claim 12, wherein said first, second and thirds layers have band gaps of 2.0ev, 1.49ev and 0.67ev respectively and are sensitive to the following wavelength ranges of up to about 600, 800 and 1800, respectively.

15. A beam splitter to be used in a solar radiation band pass filter system for producing electrical current from concentrated solar radiation according to Claim 1, said solar radiation being in the wavelength range W ranging from a wavelengths $v_1$ to $v_2$, comprising at least three sub-ranges $W_1$ including $v_1$, $W_3$ including $v_2$, and $W_2$ separating $W_1$ and $W_3$, and not including $v_1$ and $v_2$, said beam splitter being adapted for splitting said concentrated solar radiation into a first beam carrying radiation of subrange $W_2$ and directed in a first direction, and a second beam carrying radiation of subrange $W_1$ and $W_3$ directed in a second direction.
FIG. 2 (PRIOR ART)

FIG. 3A

FIG. 3B