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Concentrating and Splitting of Solar Radiation for Laser Pumping and Photovoltaic Conversion

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A solar-energy system for space application is introduced based on concentrating and splitting the solar–radiation spectrum for simultaneously laser pumping (payload) and photovoltaic energy conversion (electric power generation). Direct laser pumping by concentrated light of the appropriate spectrum band is more efficient. Higher efficiency is also obtained for concentrator solar cells in the appropriate spectrum band. Heat rejection may also be accomplished at the same time for still another spectrum band, reducing the thermal problem. High efficiency solar cells in a common system for several energy-conversion processes result in reduced weight of the system, and therefore, attractive for space applications. This article describes two configurations of two-stage concentrating and spectrally splitting systems. The concept was demonstrated for one of the configurations.

Nomenclature

C_{lb} = fraction of solar power in the spectrum band used for laser pumping of the full spectrum power
C_{pb} = fraction of solar power in the spectrum band used for photovoltaic conversion
L_{ad} = percent solar array adapter losses
L_{cpc} = percent of second-stage compound parabolic concentrator losses
P_{el} = electrical output power of the photovoltaic array, W
P_{laser} = laser output power, W
R_p, R_h = radius of the parabolic and hyperbolic mirrors, respectively, m
η_l = laser pumping efficiency for the appropriate spectrum band
η_p = solar array efficiency for the appropriate spectrum band
ρ_p, ρ_h = reflectivity of the parabolic and hyperbolic mirrors, respectively

I. Introduction

LASERS in space are proposed mainly for communication and light detection and ranging (LIDAR) systems for the near future, and for solar power transmission in the distant future.[1–4] Solar energy can be used in satellites for laser pumping by either direct or indirect conversion methods. In the direct method solar energy is directly converted to a laser beam. In the indirect method the solar energy is first converted to electricity and then supplied to a light source for laser pumping. The direct method for space was first mentioned by Young,[5] and others in the midseventies. With time, terrestrial experiments of laser pumping by the direct methods have been reported.[6–8] Also, improvement of laser performance has been achieved since the development of nonimaging concentrating and laser pumping methods. In the indirect method there are two stages of energy conversion: 1) solar to electrical energy and 2) electrical to light; both before the laser-pumping stage. Each stage of conversion is associated with losses. For this reason, the direct laser-pumping method is less complicated, more efficient, and more attractive for space application.

Although the dimensions and weight are important design parameters in terrestrial systems, these parameters play a crucial role, and therefore, may be the main constraints in space system design.

The solar array usually is one of the largest and heaviest elements in a satellite. Its size and weight are the main consideration in a feasibility study and in the final design, especially when a large amount of energy is required for the payload. In such cases the overall efficiency of the payload is one of the key parameters in the system design. In this regard, the overall efficiency is the ratio between the payload output power to the solar input power. This efficiency is significantly higher in the direct conversion method than that of the indirect one. As a result, for the same geometrical size and weight of the solar collector, the laser output power is higher.

Thermal control and heat rejection require more attention in space systems than in terrestrial applications. In the indirect laser-pumping method the thermal problems appear in three separate elements: 1) storage battery, 2) artificial light source (lamp or diode), and 3) laser medium. In the direct conversion method only the laser medium has to be cooled. Moreover, in the direct method only the appropriate band of the solar radiation spectrum may be used for pumping, reducing the amount of heat for rejection. To reduce the temperature of the laser media, the solar radiation spectrum band must be in the

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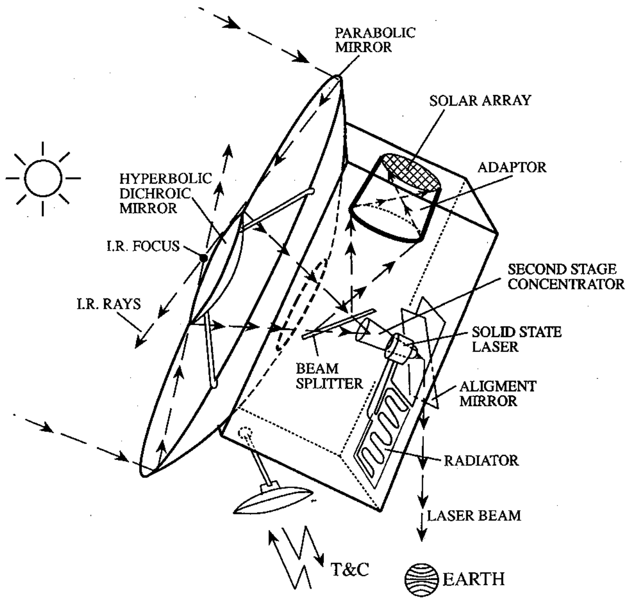

Fig. 1 Satellite-borne common system for laser pumping and photovoltaic conversion.

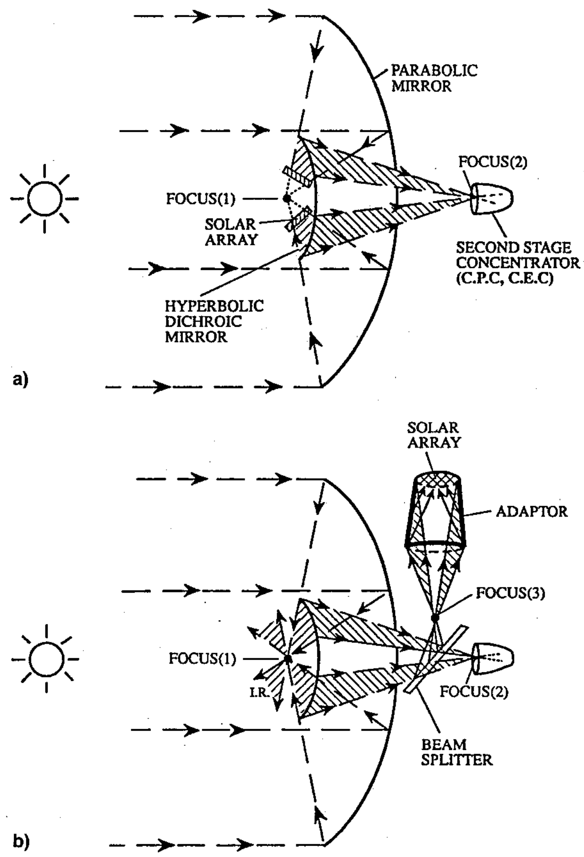

Fig. 2 Concentrating and spectrum splitting systems: a) two and b) triple foci's configurations.

range of the absorption band as near as possible to the laser emission band. Another part of the solar spectrum can be used for photovoltaic energy conversion to produce electrical power for other satellite subsystems. And still the remaining part of the spectrum may be reflected back to space, reducing thermal problems. Concentration of solar radiation is needed for laser pumping and, at the same time, to obtain higher efficiency of the solar cells.

The purpose of this study is to introduce a solar-energy system for satellites based on concentrating and splitting of the solar radiation spectrum for simultaneously laser pumping and photovoltaic energy conversion. This concept is illustrated in Fig. 1. The beam splitter divides the concentrated light of the Cassegrainian concentrator into light directed to the solar array and into light directed to the laser after additional concentration by a second-state concentrator. A satellite based on this concept requires it to be in an orbit that is exposed to the sun when laser operation is needed. A helio-synchronous orbit allows continuous laser operation.

II. Configuration of Concentrating and Spectrally Splitting Systems

The main parameters that determine the design of a system serving common laser pumping and photovoltaic conversion are 1) the collected total solar power, 2) concentration ratios, and 3) spectral ranges of the solar radiation. The solar power required for a specific satellite design is determined by the electric power consumption and by the output power of the laser. The collected power is mainly dictated by the aperture size of the first-stage concentrator, whereas the final concentration ratio depends both on the geometric parameters and optical properties of the two-stage concentrator system. The ranges of the spectral splitting depend on the energy requirement, heat rejection, and laser and solar cell types.

Solar concentrators may come in different configurations.[9,10] In space application, owing to size and weight constraints, two-stage concentrator is necessary when high solar power and concentration are simultaneously required. A two-stage concentrator allows more flexible designs since it reduces the dependence between the collected solar power and the concentration ratio. Figure 2 shows two configurations of a common system for concentrating and spectrally splitting. Both configurations are based on the concept of a Cassegrainian as a first stage and a compound parabolic (CPC) or elliptic concentrator (CEC) as a second stage for the laser pumping. The configuration, Fig. 2a, consists of two foci due to single splitting of the spectrum by the hyperbolic dichroic mirror. Focus 1 corresponds to the spectrum band designated for photovoltaic conversion, and focus 2 for laser pumping. The concentration at focus 2 is augmented by a second-stage concentrator, CPC or CEC.

The concentration level for practical concentrator solar cells is limited to several hundred suns at air mass zero[11] (AMO). This level of concentration is about 10 times lower than solid-state laser pumping requires,[12] therefore, a second-stage concentrator is needed for the laser. As for the solar cells, they are located at the back of the hyperbolic dichroic mirror at a distance from the focus. The dichroic mirror acts as a long- or short-pass filter depending on the laser and solar cell types. In spite of a moderate level of light concentration at the solar cells, heat rejection may require additional means. The triple foci's configuration (Fig. 2b) is a preferred structure from the thermal control point of view. In this configuration the IR rays are removed from the system (focus 1) by reflecting back and passing through the hyperbolic dichroic mirror acting as a long pass filter. This part of the spectrum may be further utilized for thermal to electric conversion. In the triple foci's configuration the splitting of the spectrum for the laser and for the solar array is implemented by a beam splitter. The solar cells may be located on one of the faces of the satellite not exposed to the sun (Fig. 1). This possibility and the fact that only the spectrum band needed for photovoltaic conversion is directed toward the cells may reduce significantly the temperature of the solar cells. This arrangement requires, however, an optical adapter that determines the solar cells' operating conditions as for the light concentration, uniformity, and operating temperature.

In contrast to a parabolic collector, the main focus of a Cassegrainian concentrator may be placed inside the satellite. This has practical advantages since by placing the laser inside the satellite enables better interfaces with regard to heat rejection, control of laser output power, telemetry and command, and adjustments.

In a two-stage concentrating system, the second stage may also serve another important purpose. Having an aperture of the second stage larger than the spot size at the first-stage focus 2 enables immunity against misalignment toward the sun. This advantage is expressed by the possibility of right attachment of the concentrating system and the laser to the satellite structure. The alignment toward the sun may be achieved by the existence of satellites attitude control avoiding additional alignment mechanisms, obtaining higher system reliability.

III. System Parameters Considerations

The main design parameters of the proposed system are laser type, laser output power, ranges of spectral splitting, electrical output power, concentrator dimensions, and concentrating ratio for laser and solar cells. These parameters are interrelated by complicated relationships and iterations are required before estimating the final parameter values. The advantage of the proposed approach rests in the requirement for a laser as a payload; the first step of the design calls for the determination of the type of the laser according to the mission task. Solid-state lasers using a crystal as an active element have several basic advantages in space applications: small size, high efficiency, long lifetime, and simple structure (meaning high reliability). The second step of the design is splitting the spectrum for the laser pumping based on the laser characteristics, the required laser output power, and the thermal control of the laser. Thermal control may be crucial in the design of direct pumped lasers.[11] The next step is concerned with the size of the solar power collector. The radius of the parabolic mirror is related to the laser output power by

$$P_{\text{laser}} = 1371\eta_l C_{lb}\rho_p\rho_h(1 - L_{\text{cpc}})\pi(R_p^2 - R_h^2) \tag{1}$$

Since $R_p >> R_{jh}$, the radius R_p of the parabolic mirror can be estimated for a given laser output power requirement [Eq. (1)] for known coefficients.

The electrical output power of the photovoltaic array is estimated from Eq. (2):

$$P_{\text{el}} = 1371\eta_p C_{pb}\rho_p\rho_h(1 - L_{\text{ad}})\pi(R_p^2 - R_h^2) \tag{2}$$

When the result of the calculated electrical power is sufficient, then the next step is to determine the concentration levels of the two-stage concentrators. Neglecting the back-reflected rays of the CPC, the total concentration C_t of the system may be given (with good approximation) by

$$C_t = C_{\text{cass}} \times C_{\text{cpc}} \tag{3}$$

where C_{cass} and C_{cpc} are the Cassegrain and the CPC concentration, respectively. A ray-tracing program was developed to evaluate the system performance. At the same time, the ray-tracing program was also used to estimate the accuracy of the approximation [Eq. (1)].[13] The required level of concentration depends on the laser type and its design. The theoretical upper limit of solar concentration is about 46,000. If the calculated electrical output power is not sufficient, the aperture of the parabolic mirror may be increased. In this case laser spectral band may be narrowed, reducing the required amount of heat rejection from the laser. The division of the total concentration between the first and second stages is largely dictated by the required misalignment immunity and system geometrical constraints. The expected misalignment is estimated according to the satellite attitude control performance. In the three-foci system, the location of the beam splitter limits the position of the CPC, affecting the flexibility of concentration division between the two stages.

To demonstrate the performance of the proposed system two examples are given based on the configuration of three foci (Fig. 2b). In both examples $R_p = 1$ m, $R_p^2 >> R_h^2$ [Eqs. (1) and (2)]. We assume $\rho_p = \rho_h = 0.95$, $L_{\text{ad}} = 0.1$ and $L_{\text{cpc}} = 0.1$.[13]

Example 1: The laser is an Nd:YAG type with a spectrum band of laser for pumping $700 < \lambda < 900$ nm. The expected pumping efficiency η_l for the given band is about 25%.[8] Using GaAs concentrating solar cells, the efficiency η_p in the spectrum range of $350 < \lambda < 700$ nm at 100 concentration is 30% (measured value). The solar power in the spectrum range $\lambda >$ 900 nm is reflected back to the space through the hyperbolic dichroic mirror. The power fractions for the corresponding spectrum ranges are $C_{lb} = 0.164$ and $C_{pb} = 0.42$.[14] For the previous data the laser output power [Eq. (1)] is about 140 W, the electrical output power [Eq. (2)] is about 460 W, the required heat rejection from the laser is about 420 W, and from the solar array, it is about 1000 W.

Example 2: The laser is a Cr:Nd:GSGG type with a spectrum band for pumping $450 < \lambda < 700$ nm and expected efficiency of $\eta_l = 25\%$.[8] Using concentrating Si solar cells, the efficiency η_p at 100 concentration is 25% (measured value). The appropriate power fractions are $C_{lb} = 0.32$ and $C_{pb} = 0.275$.[14] For the previous data, the laser output power is about 250 W, about 250 W electrical power, and the required heat rejection from the laser and from the solar array is about 750 W for each.

In the previous examples the R_p was assumed to be 1 m. By scaling this radius one may easily estimate the different powers that can be obtained or, for a required power, one may calculate the necessary radius.

IV. Realization of a Cassegrainian Concentrating and Spectrum Splitting System

To demonstrate and investigate the performance of the proposed system, a Cassegrainian concentrating and spectrally splitting system of configuration Fig. 2a was designed and realized, as shown in Fig. 3. The system is attached to a two-axis gimbal, tracks the sun automatically by means of stepper motors, and is controlled by a personal computer. The tracking accuracy is 0.5 mrad measured during a long time (weeks) and the accuracy for a short time (day) is better than 0.1 mrad. The diameter of the parabolic mirror is 600 mm made of alu-

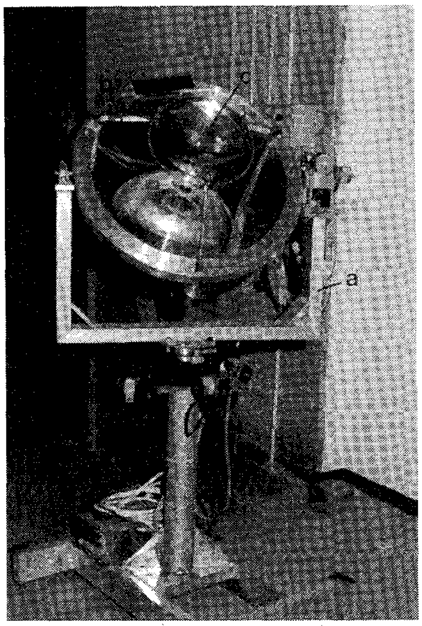

Fig. 3 Concentrating and spectrum splitting demonstration system: a) two-axis gimbals for automatic sun tracking, b) parabolic aluminum diamond turned mirror, and c) hyperbolic dichroic mirror.

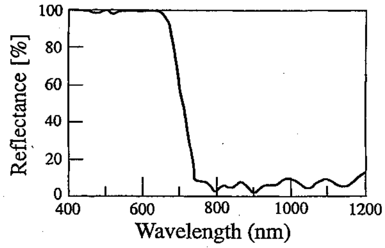

Fig. 4 Reflectance of the hyperbolic–dichroic mirror for incident angle of 45 deg.

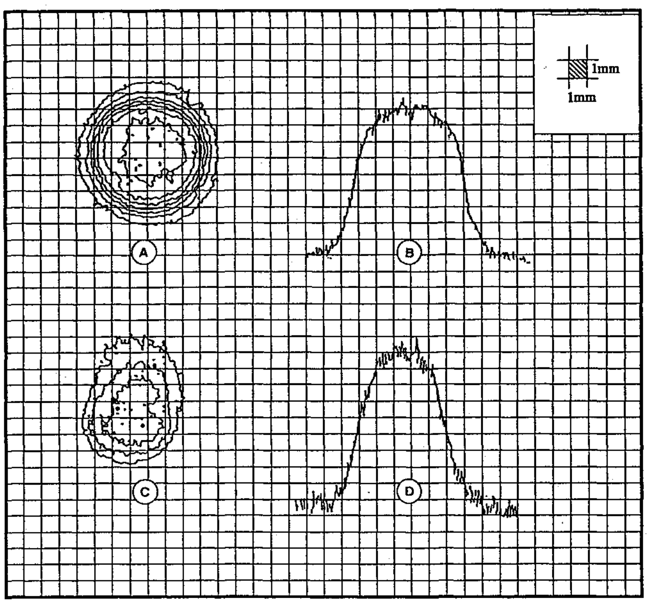

Fig. 5 Measured solar spots sizes and relative intensity of concentrated solar fluxes at system foci of Fig. 2a: focus 1 (A and B) and focus 2 (C and D).

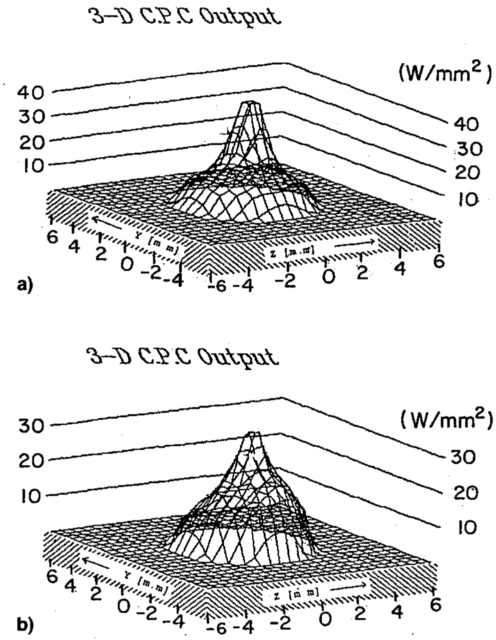

Fig. 6 Distribution of spot light intensity at the CPC output: a) with no misalignment and b) with misalignment of 3 mrad.

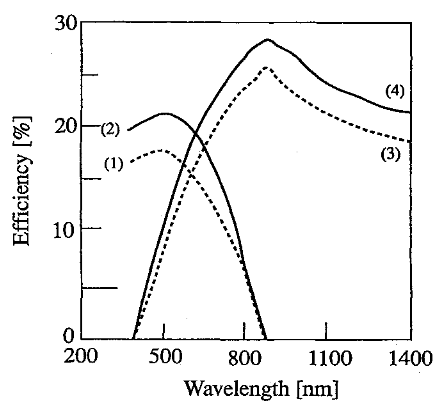

Fig. 7 Efficiency of GaAs concentrator cell at different spectral bands (cuton = 1, 2 and cutoff = 3, 4); and for AMO (1, 3) and AM1.5 (2, 4) spectrum. The concentration is 100 (at AMO).

minum diamond turned. The diameter of the hyperbolic dichroic mirror is 268 mm and the cutoff wavelength is 700 nm. The measured concentration of the Cassegrain is 6500.

The hyperbolic–dichroic mirror was manufactured by a low-cost process developed for this purpose. A circular planar glass set on a hyperbolic shape of a steel form was put into an oven at glass annealing temperature. The glass obtained the hyperbolic shape of the form; then it was coated with multilayers of TiO_2 and SiO_2. The reflectance characteristic of the hyperbolic–dichroic mirror is shown in Fig. 4. The distribution of power intensity of the concentrated solar radiation at the foci (shapes of solar spots) of the system (Fig. 3) were measured by a charge-coupled device camera and analyzed by image processing. Some of the results are shown in Fig. 5 at focus 1 (A and B) and focus 2 (C and D) for the foci in Fig. 2a. The effect of the dichroic mirror on the symmetry and the spot shape is apparent. Misalignment and production inaccuracy of the dichroic mirror resulted in distortion of the spot. These results (power and concentration) were compared to the calculated values based on the previously mentioned three-dimensional ray-tracing program that was developed for analyzing the performance of a two-stage concentrator that included a CPC as a second stage for the purpose of laser pumping. The effect of sun-tracking misalignment on the distribution of the solar power at the output of the CPC is shown in Fig. 6 based on the ray-tracing program.

The developed demonstration system was also used for Si and GaAs concentrator solar cell studies at different concentrations of solar radiation, for different bands of the solar spectrum (using a wheel-filter) and at different temperatures. The variation of cell efficiency of a GaAs cell with spectral band for AMO (1, 3) and AM1.5 (2, 4) is shown in Fig. 7. The efficiency here is defined as power output divided by the filtered incident power. The efficiency is calculated for short wave spectral band (short-pass filter) bounded by a cutoff wavelength (3, 4) and for along wave spectral band (long-pass filter) bounded by a cuton wavelength (1, 2). In all measurements the short circuit current is kept constant at a value, corresponding to $C = 100$ at AMO and full spectrum.

V. Conclusions

Several solar energy conversion processes can be utilized simultaneously using a common collector if the solar radiation is appropriately spectrally split. Weight reduction and efficiency improvement can be achieved using this approach, therefore they are attractive for space applications. The efficiency improvement is a result of using the appropriate spectral band for the particular process. Solar concentration also contributes to an increase in efficiency. In some energy conversion processes a high concentration is essential for the feasibility of the process such as for laser pumping. When a solar pumped laser is considered for a space system, the approach for using a common concentrating collector as an energy source for the laser and for photovoltaic energy conversion is a natural choice. The splitting of the solar spectrum into different spectrum bands for the laser and the solar cells may be accomplished by a hyperbolic dichroic mirror, which is a part of the Cassegrain concentrator in one configuration or, by an additional beam splitter in another configuration. Heat rejection may also be obtained at the same time for still another spectrum band, reducing the thermal problem. Conversely, the heat may be used for thermoelectric conversion, utilizing most of the spectrum for three energy conversion processes.

This article describes two configurations of a concentrating and splitting system. The concentration is obtained by two stages. The first stage is a Cassegrain made of a parabolic mirror and a hyperbolic dichroic mirror. The second stage is a CPC (or CEC). Estimated values of the laser output power, photovoltaic array output power, heat rejection required from the laser and from the solar cells are illustrated in two design examples. The realization of the proposed approach was demonstrated for one configuration made of parabolic and hyperbolic mirrors. This concentrating system was attached to a two-axis gimbal that tracks the sun automatically. This system was also used for solar cell studies at different concentration ratios, for different spectrum bands and at different temperatures. A ray-tracing program was also developed to compare the measured and calculated powers, concentration ratios, and sun spot shape and size.

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