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A novel agricultural photovoltaic system based on solar spectrum separation

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ABSTRACT

Agriculture photovoltaic (APV) is a promising and trend-setting technology which initiated an innovative industrial revolution. It is the combination of photovoltaic power generation and simultaneous agricultural activities on the same land. Existing approaches for agriculture photovoltaic install solar panels high above the farm field. The solar panels still block majority of sunlight and hinder efficient plant growth. In this paper a competitive edging development is present in the APV field that is unique and revolutionary. Combining concentration photovoltaic (CPV) and diffractive interference technology, a new system for agriculture photovoltaic has been successfully demonstrated. This system allows agricultural use and electricity generating on the same land in a very cost-effective way. The invention of semitransparent glass panels is discussed, which transmit only the light necessary for plant growth. A thorough mathematical analysis is performed to elaborate the theoretical background of the presented agriculture photovoltaic system. It allows optimizing the design layout and related CPV concepts. The test results of plants growing underneath the innovative agriculture photovoltaic system are shown and discussed. The average efficiency of the agriculture photovoltaic system has reached more than 8% and the average efficiency of the CPV system is 6.80%.

1. Introduction

Solar light is the best source for green renewable energy with the advantage of very limited environmental impact. It is regarded as one of the most promising and effective way to solve the energy crisis. Large-scale PV projects require a huge area of land, which consequently can no longer be used for agricultural applications. This is a problem for the photovoltaic industry in many countries. Farmers would like to use their lands for agriculture and PV projects simultaneously.

Only 10% of the sunlight is used for efficient plant growth. It is driven by two relative narrow wavelength regions: a red wavelength band around 660 nm and a blue wavelength band around 450 nm (Chen and Blankenship Robert, 2011). Within these two wavelength bands lies the absorption peaks of chlorophyll *a* and chlorophyll *b* of plants. They are the fundamental wavelength bands for photosynthesis. Plants have a similar genetic structure leading to similar complex biochemical photosynthetic functions. Consequently, almost all plants require the same narrow wavelength bands in the blue and red-light region (Ian et al., 2004).

Wavelength division multiplexing allows for the generation of narrow wavelength bands (Charles, 1990). It is a multiplexing technique leveraging filters, where neighboring wavelength channels can be specifically combined and separated into narrow wavelength bands. Applying this concept to agriculture photovoltaic, a part of the sunlight can be reflected, while another part can be transmitted. It is possible to design a filter which matches the transmission spectrum accommodating plant photosynthesis. Sunlight is split into blue and red wavelength bands which are transmitted for plants, while all other wavelength bands are reflected and focused on solar cells for power generation.

Spectrally selective beam filtering of sunlight is also used in hybrid photovoltaic-thermoelectric systems (Imenes and Mills, 2004). Investigations have been reported to improve the efficiency of hybrid photovoltaic-thermoelectric (TE-PV) by separating the sunlight in a specific way (Deng et al., 2013; Ju et al., 2012). A dielectric or metal film is necessary, which consists of multiple thin layers. The film allows a defined transmission of sunlight suitable for TE-PV systems (Enok et al., 2016; Sibin et al., 2017). Concentration photovoltaic (CPV) systems are like TE-PV systems. Therefore it can be studied in literature how to tailor the design layout of the multiple layer dichroitic film

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Nomenclature

a	the logarithmic ratio of the short circuit current and the reverse saturation current
c	the speed of light (m/s)
d_i	thickness of layer i of the thin film(μm)
e	electron charge (C)
FF	fill factor
h	Planck constant (J·s)
I_{ph}	photocurrent (A)
I_{sc}	short-circuit current (A)
I_0	saturation current (A)
k	Boltzmann constant (J/K)
n_i	refractive index of layer i of the thin film
n_e	the number of excited electron
n_{ph}	the number of absorbed photon
P_{ph}	sun light radiation power (W)
P_m	maximum power point (W)
P	output power of solar cell (W)
iq	transfer matrix of layer i of the thin film
Q	transfer matrix of the thin film
R	reflectivity of film
RS	absolute spectral response (A/W)
T	temperature (K)
V	voltage of solar cells (V)
V_{oc}	open circuit voltage of solar cells (V)
λ	wavelength (nm)
η	the external quantum efficiency of solar cells
Φ_i	the phase angle of layer i of the thin film

(Vorobiev et al., 2006; Chávez-Urbiola et al., 2012; Agrawal, 2012; Chauhan and Agrawal, 2016). It can be freely determined which wavelength bands will be separated and this gives a unique advantage to modulate the wavelength splitting ratio. This enables the capability to specifically fine tune for efficient growth of individual plants and efficient power generation for selected solar cells.

A innovative APV-system is presented in this paper that considers both efficient solar power generation and efficient agricultural planting. The APV-system allows for simultaneous highly optimized power generation and highly optimized plant growth. By reflecting the NIR, the temperature and therefore the evaporation of water during summer days can be substantially reduced.

2. Agriculture photovoltaic

Agriculture photovoltaic allows for both solar based electricity generation and agricultural use of the same area of land. Plants and crop growth can be sustained even though the land is filled with solar panels. It represents solar photovoltaic for sustainable agriculture and rural development. It can be seen in Fig. 1a that the concept of agriculture photovoltaic merges smoothly into the interconnection between consumer's energy usage and storage, energy purchasing agreements with local residential and industrial estates and energy provision to the power grid distribution system from operators (Pandey et al., 2016).

There are currently two main "traditional" agriculture photovoltaic solutions, both domestic and international: One is realized by installing "mosaic" or strip type of crystalline silicon photovoltaic panels, which are placed in the higher upper region (+5m) of the crop field (Fig. 1b) (Obergfell et al., 2013). They allow for some sunlight to hit the ground, but the majority of the sunlight hits the photovoltaic panels to generate electricity. This geometrically designed spectral photovoltaic agricultural layout means that the crystalline silicon cells block the sun from reaching the farmland during the plant growing cycle. The winter sun is dimmer and this agriculture photovoltaic solution can be harmful for plant growth. The uniformity of sunlight and the shadow casting is a problem making it difficult to achieve optimal land production.

Another "traditional" agriculture photovoltaic solution targets greenhouse roofs. The integration of the photovoltaic in greenhouses has been described by many papers. In some of the publications, solar cell panels are used to partly cover the greenhouse roof (Cossu et al., 2014; Yano et al., 2009; Yano et al., 2010). Again, shade of the solar panels affects the plant growth negatively. For example tomatoes grown under the greenhouse roof with solar panels have significantly lowered masses and later ripening times compared to traditional greenhouse crops (Marrou, 2013). It was also demonstrated that the issue of shade affects the quality of the fruit which leads to a lower yield (Scognamiglio et al., 2015). Many trials and formulations were examined to get the best balance between optimal photovoltaic power generation and optimal plant growth. The studies show that in order to not significantly affect lettuce yield, the light in the greenhouse should not be reduced by more than 30% (Kadowaki et al., 2012; Marrou et al., 2013). In generally, wherever the crops yield is given priority, the percentage of the greenhouse area covered by solar panels should be less than 10% (Pérez-Alonso et al., 2012; Ureña-Sánchez et al., 2012). However, this severely limits the efficiency of photovoltaic generation and wastes valuable light resources for solar power generation.

(a) (b)

Fig. 1. (a) The basic principles of agriculture photovoltaic; (b) current solution for agriculture photovoltaic by implementing mosaic type of solar panels structures high above the farmland.