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A novel concentrator with zero-index metamaterial for space solar power station

Jin Huang *, Xue-mei Chu, Jian-yu Fan, Qi-bao Jin, Zhu-zhu Duan

School of Electromechanical Engineering, Xidian University, Xi'an, Shanxi 710071, China

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Abstract

Space solar power station (SSPS) is a comprehensive system that continuously collects solar energy in space and transmits it to ground with a wireless power transmission (WPT) system. These systems have great potential to provide large-scale energy. To increase the efficiency and reduce the weight and cost of the photovoltaic (PV) components, a huge light-weighted concentrator was introduced in the latest SSPS concepts, such as integrated symmetrical concentrator (ISC) and arbitrarily large phased array (ALPHA). However, for typical SSPS running in Geostationary Earth Orbit (GEO), the sunlight direction varies with time, leading to a great challenge for concentrator design. In ISC, the two-dimensional mast is used to realize sun-tracking. However, a multi-thousand-ton structure is difficult to control precisely in space. For this reason, ALPHA comprises a large number of individually pointed thin-film reflectors to intercept sunlight, mounted on the non-moving structure. However, the real-time adjustment of the thousands of reflectors is still an open problem. Furthermore, the uniformity of the time of the power generation (UTPG) is another factor evaluating the system. Therefore, this paper proposes a novel concentrator based on zero-index metamaterial (ZIM) called Thin-film Energy Terminator (SSPS-TENT). This will aid the control of the massive reflectors while avoiding the rotation of the overall system, the control of the massive reflectors and the influence of the obliquity of the ecliptic. Also, an optimization design method is proposed to increase its solar energy collecting efficiency (ECE) and flux distribution (FD). The ray-tracing simulation results show that the ECE is more than 96% of the day. In terms of the FD, the uniformity varies from 0.3057 to 0.5748. Compared with ALPHA, the UTPG is more stable.

Keywords: SSPS; Concentrator; ZIM; Ray-tracing; Energy collecting efficiency; Flux distribution

1. Introduction

As demand for global energy has increased and environmental concerns have become more pressing, solar energy has drawn increasing attention over the last decades. The average intensity is high and stable in space, with its immunity to night, season and weather. Around the Geostationary Earth Orbit (GEO), the available solar energy intensity is about 1368 W/m^2, ten times greater than that on the ground. Therefore, the space solar power system (SSPS) is regarded as a potential option for terrestrial use with the continuing decrease of finite energy reserves on the earth (Mankins, 2001; Hou and Wang, 2014).

In 1968, the concept of the SSPS was invented by Peter E. Glaser (Glaser, 1968), who proposed two satellite conversion systems placed in GEO to collect solar energy and transmit it to the earth. Recently, the development of key technology has increased the feasibility of SSPS with advancements such as photo-voltaic (PV) technology (Glenn; Ma, 2013), wireless power transmission (WPT) (McSpadden and Mankins, 2002; Yoshiharu et al., 2011; Deng et al., 2015), thermal control technology (Li, 2014; Ballestrin, 2002) and new materials (Moitra et al., 2013). SPSS consists of three main parts: a light-collecting system, an energy converting/transmitting system in the space seg-

* Corresponding author. Fax: +86 029 88203040.
E-mail address: jhuang@mail.xidian.edu.cn (J. Huang).

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ment and a receiving system on the earth. Among these, the light-collecting system includes non-concentrated and concentrated patterns. In the non-concentrated light-collecting system, the PV arrays need to be controlled to track the sun with a rotation mechanism. Also the high-power collection results in a huge area of the PV cells and low utilization efficiency, which increases the devices and launching costs as well. Typically, it includes the NASA/DOE reference model (Department of energy and NASA, 1978), the solar-sail tower model (Seboldt et al., 2001) and the Tether SPS proposed by Japan (Sasaki et al., 2007). Internationally, the concentrated light-collecting system is recognized as the developing tendency of SSPS. In this pattern, on one hand, the redundant PV devices can be reduced to decrease the costs. On the other hand, the total mass of the thin-film reflectors is far lower than PV devices, which reduces the area of the PV array effectively, as well as the mass of the whole system and launching costs. The concentrator PV (CPV) technology (Feingold and Carrington, 2003) is adopted in SSPS with this pattern. Recently, more and more SSPS concepts with concentrators are proposed, such as the modular symmetrical concentrator (MSC) (NSSO, 2007), integrated symmetrical concentrator (ISC) (Jin et al., 2015) and arbitrarily large phased array (ALPHA) (Mankins, 2012).

Among the recent concepts, ISC collects sunlight by two segmented clamshell primary mirrors located on the end of a two-dimensional mast. Two centrally-located PV arrays receive the reflected energy. The mast, PV arrays and transmitter rotate as a unit to track the sun, which could be realized by trajectory planning of the solar tracking (Jin et al., 2015). The power management and distribution (PMAD) masses are reduced. Also, the influence of the seasonal obliquity of the ecliptic can be adjusted by the rotational capability. ALPHA was presented by Mankins in 2012. This concept is bio-inspired, modular and light-weighted and comprises a large number of individually pointed thin-film reflectors to intercept sunlight, mounted on a non-moving structure. Each reflector reflects sunlight to fall into the PV arrays integrated in the sandwich module (Jaffe et al., 2012; Jaffe and Mcspadden, 2013).

However, for both MSC and ISC, the sunlight-collecting structure needs to be precisely controlled to track the sun. Because it is large scale and weighs thousands of tons, the implementation is currently very difficult. For this reason, ALPHA was proposed by Mankins, comprising a large number of individually pointed thin-film reflectors to intercept sunlight, which would be mounted on a non-moving structure. None of the major components are more massive than 100–300 kg, which avoids the issue of ISC and MSC. However, presuming an 8.65 GW collecting power in space and 2 GW power level delivered to the earth (Yang et al., 2014), the structure will require 4662 individually-controlled mirrors (Mankins, 2012). The highly complex nature of the required controls is still an open issue.

To solve these problems, this paper proposes a new concentrator system based on zero-index metamaterial (ZIM) with the property that redirects the energy propagation direction. Furthermore, alternative material with the same property can be chose to ensure the energy collecting implementation, such as two-dimensional metamaterials—metasurfaces (Chen et al., 2016; Shi et al., 2014; Gholipour et al., 2013; Li and Yu, 2013; Pfeiffer and Grbic, 2013). The modeling and simulation are demonstrated in specific parameters of the structure according to the basement 8.65 GW. Then, energy collecting efficiency (ECE) and flux distribution (FD) are optimized for the specific structural parameters. Finally, the ECE and FD of a 24 hours day are analyzed to validate the performance of the proposed concentrator and compared with ALPHA.

2. The SSPS-TENT design project

A novel concept is proposed to address the issues mentioned above based on ZIM with low loss and high transmittance. ZIM is a specific category of metamaterials that has undergone tremendous development in recent years, and has potential applications in many fields (Pavel et al., 2013; Su et al., 2012; Xiang et al., 2014; Wei et al., 2013; Cai and Vladimir, 2010). Some extraordinary optic phenomena and unusual transmission properties have been observed (Zhong et al., 2014; Alu et al., 2007), such as the focusing and directive emission of electromagnetic waves (Luo et al., 2012; Vito et al., 2011; Enoch et al., 2002). Nowadays, different ZIMs have been discovered to satisfy different applications. Low transmittance and high reflection caused by oblique incidence through ZIM have been combated with different measures (Chen et al., 2016; Luo et al., 2013; Sun et al., 2009; Xu and Chen, 2011), such as by superimposing a plasmonic thin film in the material (Feng, 2012). Therefore, with the extension of the transmission angle and working efficiency, the optical ZIM with low loss and high transmittance has strong potential application prospects with the process of the research.

To deliver the solar energy to the earth, TENT would typically be based in GEO. The attitude of TENT in GEO is shown in Fig. 1. The conceptual visualization of TENT is illustrated in Fig. 2.

2.1. Detailed concept architecture

As shown in Fig. 2, the detailed architecture of TENT is mainly comprised of four elements:

(1) A large sunlight-collecting non-moving structure with ZIM;
(2) A sandwich module integrated by PV arrays, microwave devices and a transmitting antenna (pointing to the earth);
(3) A small-sized flexible reflector;