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Performance analysis of a mirror symmetrical dielectric totally internally reflecting concentrator for building integrated photovoltaic systems

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HIGHLIGHTS

- The process of fabricating an MSDTIRC is presented.
- The electrical and optical performances are investigated.
- The MSDTIRC is capable of providing a maximum gain of 4.2×.

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ABSTRACT

This paper presents a mirror symmetrical dielectric totally internally reflecting concentrator (MSDTIRC). Here, its electrical and optical performances are investigated for building integrated photovoltaic applications. This concentrator is designed to tackle two issues: (i) providing sufficient gain in order to increase the electrical output of a solar photovoltaic (PV) system and (ii) reducing the size of the PV cell needed, hence minimising the cost of the system. These experiments carried out had the objective of investigating the characteristics of the cell with the concentrator, the angular performance of the structure, and the effect of temperature on the cell. In each case, the current–voltage (*I*–*V*) characteristics and the power–voltage (*P*–*V*) characteristics are plotted and analysed. An outdoor experiment was also conducted to verify the results obtained from the indoor experiments. The MSDTIRC-PV structure is capable of providing a maximum power concentration of 4.2× when compared to a similar cell without the concentrator. The deviation of the concentration factor from the geometrical concentration gain (4.9×), is mainly due to manufacturing errors, mismatch losses and thermal losses.

1. Introduction

Solar energy is one of the renewable energy sources that has greatest potential. It has been reported that, by 2011, solar photovoltaic (PV) had been introduced in more than 80 countries and was considered the fastest growing power generation technology [1]. In 2011 alone, a staggering 30 GW was installed globally making the global total reach 70 GW – an increase of 79% when compared with the installation carried out in 2010 [1]. The European Union (EU), at the time, dominated the solar PV market (see Fig. 1), led by Germany and Italy, amounting to about 37.8 GW of the total installed PV [1]. The installed PV capacity is dominated by grid-connected installations, mainly due to the introduction of feed-in tariff schemes [2]. The off-grid sector on the other hand has experienced a declining share each year [1].

Recently, solar PV started to gain popularity in building integration applications [3]. It was estimated that between 20% and 40% of the world's energy consumption is consumed in commercial and residential buildings [4]. This figure is projected to experience an upward trend with an increase in the world population, a growth in building services and comfort levels as well as a rise in time spent in a building [4]. For this reason, governments worldwide are looking to design green buildings that can be energy efficient and independently generate energy [5]. Especially in urban

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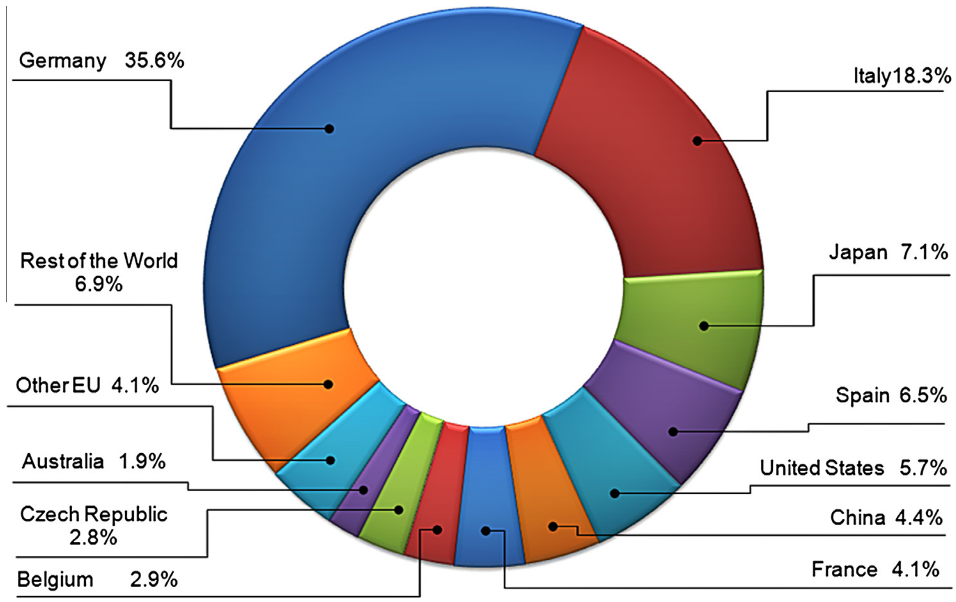

Fig. 1. Top 10 global PV market in 2011. Adapted from [1].

environments, solar PV has potential not only for roof mounting, but also for integration in any building parts; i.e. the roof, facades and curtain walls, depending on the location and design of the building [6]. With an improved awareness on renewable energy, substantial financial incentives from governments and the downward trend of solar PV cost, the penetration of building integrated photovoltaic (BIPV) systems is expected to rise sharply globally. China for example started the largest BIPV project in July 2010, with a capacity of 6.68 MW [7].

To further reduce the cost of the BIPV system, an application of PV devices is being introduced, known as the concentrating photovoltaic (CPV) system [8]. The CPV system utilises inexpensive optical device to concentrate light from a large entrance aperture into a smaller exit aperture where a solar cell is attached [8]. Some of the benefits of the CPV systems include: a reduction in total cost of the system due to minimal usage of expensive PV material and a higher electrical output due to the increase in solar flux intensities at the solar cell [8–10].

Since 1970s, there are various CPV designs proposed by researchers worldwide. Sellami et al. [9] proposed a CPV system called the Square Elliptical Hyperboloid (SEH) which has the potential to be integrated in double glazed windows. With a concentration value of 4× and acceptance angle of 120° (±60°), an optical efficiency of 40% was recorded. Mammo et al. [11] investigated a reflective 3D crossed compound parabolic-based photovoltaic module (3D CCPC PV). This design is capable of generating a maximum power concentration of 3.0× when compared to similar type of non-concentrating module. Sarmah et al. [12] constructed a CPV system known as the Asymmetric Compound Parabolic Concentrator (ACPC) which generates a maximum power of 1.6 W, 2.1 times the power generated by the non-concentrating counterpart.

With a recent downwards trend of solar module price worldwide, the CPV system could still offer some added advantages; namely illumination, hot water and space heating generation, and ventilation. Illumination is achieved by implementing transparent/semi-transparent solar concentrators which allows the daylight to penetrate into the building hence reducing the energy requirement of the building [13]. Among the applications include sky lighting, windows and glass facades [3].

To ensure that the CPV system is working at an optimum level, it is cooled either by water or air. Cooling using water is carried out by attaching a pipe at the bottom of the PV cell, where the heated water is collected and could be used as hot water and for space heating [14]. Cooling by air is achieved by combining the laminar flow effect and the chimney effect, creating good air ventilation for the building [14]. These processes allows the CPV system not only to generate electricity, but also the capability of producing hot water, space heating, ventilation and illumination, which further reduces the electricity requirement in a building, making it more desirable [14–17].

This paper proposes a new type of solar concentrator, known as a mirror symmetrical dielectric totally internally reflecting concentrator (MSDTIRC), for use in BIPV systems. Section 2 describes the fabrication process of an MSDTIRC, followed by the experimental setup, which is explained in Section 3. The experimental results are presented and discussed in Section 4. Finally, conclusions are presented in Section 5.

2. Fabrication of MSDTIRC

The MSDTIRC is a new variation of DTIRC and is patent pending [19]. This concentrator is able to achieve different field of views on different planes. In contrast to the rotational axis symmetrical DTIRC proposed by Ning et al. [18], this new design generates a mirror symmetry design in four axes parallel to the base of the concentrator. The process used to fabricate an MSDTIRC is summarised in Fig. 2.

A MATLAB® based program has been developed to create the MSDTIRC. The MSDTIRC uses the DTIRC based on the phase conserving method (PCM) [18] as the design's foundation and the process to produce this design is detailed out in Ref. [19]. Unlike the 3-D rotationally symmetry DTIRC that has a smooth dome shaped front surface entrance, this design has a varying front surface with four axis of mirror symmetry (see Fig. 3d). Depending on the input parameters, the front surface will be different from each design [19]. Another important characteristic of this concentrator is its square exit aperture, as presented in Fig. 3e. According to Sellami and Mallick [20], from the manufacturing point of view, it is desirable and easier to fabricate a square/rectangular cell, unlike a circular cell employed in a rotationally symmetry design.