

Article

Structural Design and Optimization of Radio-Photovoltaic Cells Based on Waveguide Light-Concentration Array Structure

Tongxin Jiang ^{1,2,*} , Yincai Liu ², Na Wang ^{3,*}, Chen Wang ⁴ and Haisheng San ^{4,*} 

¹ School of Integrated Circuit Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

² School of Electronics and IoT, Chongqing Polytechnic University of Electronic Technology, Chongqing 401331, China; liuyincai112233@foxmail.com

³ School of Electronic and Electrical Engineering, Ningxia University, Yinchuan 750021, China

⁴ School of Intelligent Manufacturing, Xiamen University, Xiamen 361005, China; wangchen68@stu.xmu.edu.cn

* Correspondence: jiangtongxin@uestc.edu.cn (T.J.); nwang@nxu.edu.cn (N.W.); sanhs@xmu.edu.cn (H.S.)

Abstract

The performance of radio-photovoltaic cells (RPVCs) depends on the radiation source, energy deposition, and radioluminescence collection. This study examines a waveguide light-concentration array (WLCA) composed of GAGG:Ce columns with radiation source material loaded into the inter-column gaps. The array increases the interfacial area between the source and the scintillator and allows irradiation from several directions. A source-thickness scan identifies 120 μm as a candidate near the plateau of the emitted-electron yield. In the structural calculations with 120 μm gaps, approximately 31.8% and 75.8% of the initial energy is deposited in GAGG:Ce for representative ^{90}Sr and ^{90}Y electron energies, respectively. The ^{90}Sr deposited-energy fraction increases from approximately 16.2% in the conventional sandwich (CS) structure to 31.8% in the WLCA. Compared with the CS structure, the WLCA increases source-energy utilization efficiency by 96.3%. In addition, the radioluminescence emission of the WLCA structure is superior to that of the CS structure, while the photon emission is more concentrated. These results identify the WLCA structure as a promising strategy for improving radio-photovoltaic energy conversion and extending the applicability of long-life isotope power sources.

Keywords: radio-photovoltaic cell; waveguide light-concentration array; GAGG:Ce; ^{90}Sr ; Monte Carlo simulation

1. Introduction

Long-lived, maintenance-free micropower sources are required for wireless sensors and monitoring systems deployed in deep space, the deep sea, polar regions, and other inaccessible environments [1,2]. Unlike chemical batteries and externally illuminated photovoltaic devices, nuclear batteries derive energy continuously from radioactive decay and can operate over timescales governed primarily by the isotope half-life [3,4]. This combination of operational longevity, compactness, and stable output is well suited to unattended equipment. Nuclear batteries have been coupled with capacitors to power wireless sensor nodes [5].

Nuclear batteries are classified by their energy-conversion mechanism [6]. Radioisotope thermoelectric generators convert decay heat [7], whereas radiovoltaic cells generate electron-hole pairs directly in a semiconductor and may undergo irradiation damage [8,9]. A radio-photovoltaic cell (RPVC) employs a phosphor or scintillator between the radiation



Academic Editor: Frédérique Ducroquet

Received: 29 August 2026

Revised: 29 September 2026

Accepted: 2 October 2026

Published: 8 October 2026

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source and the photovoltaic (PV) cell. Decay energy is converted into radioluminescence (RL) and then into electricity, thereby avoiding direct irradiation of the PV junction by decay particles [10,11]. RPVC efficiency depends on radiation particle emission, particle transport, energy deposition, RL generation, photon transport and extraction, and photovoltaic conversion. Losses include radiation source self-absorption, particle escape, incomplete energy deposition, nonradiative relaxation, optical self-absorption, optical trapping, interface reflection, and PV dark current [12]. Because these stages are coupled, the radiation source, scintillator, optical path, and PV collection area must be optimized as a system.

The selection of a scintillator depends on both the energy of decay particles and the optical transport distance. ZnS-based phosphors provide strong RL and radiation tolerance [13,14], whereas halide scintillators (such as CsI:Tl) offer high light yield but require moisture-resistant packaging [15]. Oxide crystal scintillators, including GAGG:Ce [16] and GYAGG:Ce [17], have high density [18], high light yield [19], and radiation tolerance [20]. The refractive index of GAGG:Ce (approximately 1.96) supports waveguiding but narrows the escape cone at a crystal-air interface [21,22].

Conventional sandwich (CS) structures place the radiation source, phosphor layer, and PV cell in sequence [23], causing energy losses during both decay particle interception and photon collection [24]. Interface engineering can alleviate these losses [25,26], but it does not avoid the limitations of the planar geometry. The waveguide light-concentration (WLC) structure improves particle utilization and guides RL toward edge-coupled PV cells. The prototype achieved an energy-conversion efficiency of 2.96% and a maximum output power of 48.9 μW [27]. Nevertheless, the planar WLC structure retains long lateral photon paths and limited source-loading volume [28,29]. Therefore, it is necessary to further optimize the structure in order to achieve a shorter photon transmission path and a larger loading volume for the radiation sources.

Here, a waveguide light-concentration array (WLCA) composed of columnar GAGG:Ce crystals is proposed. MCNP calculations examine source thickness, energy deposition, source self-absorption and radiation escape. Geant4.11.3.0 is used to illustrate electron and scintillation-photon transport. The energy absorption and conversion patterns of the CS, WLC, and WLCA structures were compared under the same particle incidence conditions, and the RL emission characteristics of these three structures were analyzed. The work is a computational design study intended to guide fabrication and experimental evaluation.

2. Materials and Methods

2.1. Structural Design and Comparative Mechanism

Figure 1 compares the CS structure, the WLC structure, and the proposed WLCA structure. The comparison illustrates differences in radiation source loading, particle interception and optical collection geometry. Equal source activity and equal package volume are distinct comparison conditions. The CS structure consists of a radiation source, a phosphor layer, and a PV unit arranged sequentially, as shown in Figure 1a. With isotropic 4π beta emission, approximately half of the emitted beta particles are initially directed toward the RL layer in the ideal planar limit; source self-absorption, backscattering, and inactive gaps can reduce the useful fraction further. Energy deposited in the phosphor produces RL, and a photon must cross the interface between the phosphor layer and the PV cell. Therefore, the architecture has geometric collection losses at both the decay-particle transport and radioluminescence-collection stages. Increasing scintillator thickness can improve the energy deposition ratio, but it also lengthens the optical path and aggravates self-absorption. Thus, the CS structure cannot be optimized by thickness alone.

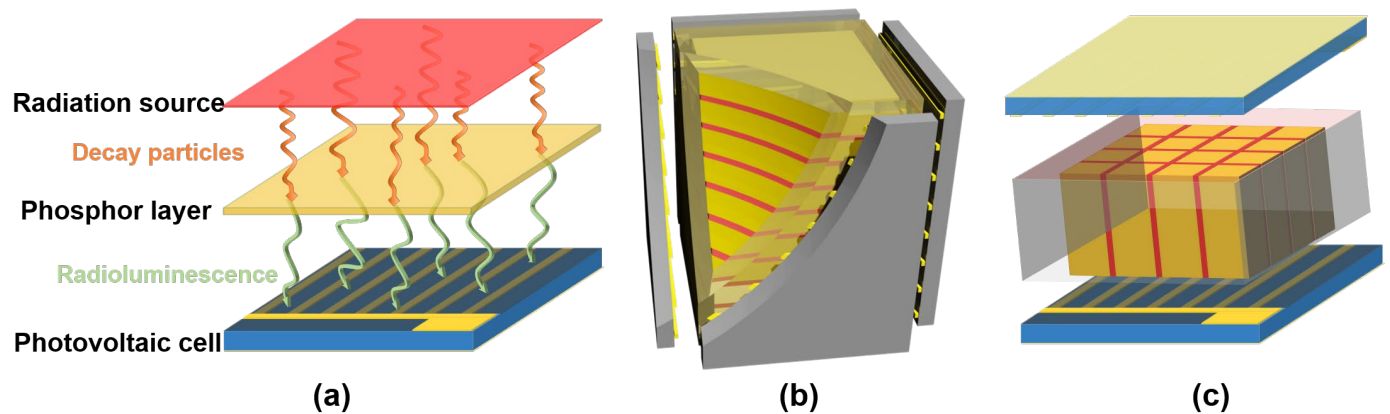


Figure 1. Schematic diagrams of the energy-conversion architectures. (a) CS structure, (b) WLC structure, and (c) WLCA structure.

The WLC structure (Figure 1b) uses the high refractive index of GAGG:Ce to confine RL and redirect it toward edge-mounted PV cells. Interleaving radiation source layers with scintillation waveguides allows decay particles emitted from the radiation source layer to enter the GAGG:Ce scintillator, reducing the one-half loss in the CS structure. However, as the module width increases, the mean lateral path to an edge grows and photons undergo more reflections before collection. Bulk reabsorption, surface scattering, and leakage through the source-facing interface therefore become increasingly important. Because the source remains confined to planar gaps, source activity does not increase in direct proportion to the total scintillator volume.

The WLCA structure (Figure 1c) consists of an ordered array of columnar GAGG:Ce crystals, with ^{90}Sr -containing source material occupying the inter-column gaps. Interior radiation source regions border several scintillator faces, allowing electrons emitted in different directions to enter GAGG:Ce. The proposed collection surfaces are the two column ends. The increased source–scintillator interface area supports multidirectional excitation, along with shorter optical paths to the PV cells. Additional optical interfaces and nonuniform excitation near the array edges must also be considered.

Table 1 presents an idealized geometric comparison, rather than measured or transport-derived efficiencies. The relative light output reported in the table is obtained by multiplying the assumed source-activity, particle-interception and light-distribution factors; for CS, WLC and WLCA, this gives 1, 2 and 6, respectively. The collection factor is a geometric descriptor and is not multiplied again. The areal light-output values concern the emitting area, not the volumetric electrical power density. Source self-absorption, optical attenuation, boundary losses and imperfect PV coupling are excluded, so 100% does not imply loss-free transmission. Accordingly, Table 1 establishes the geometric potential, whereas the Monte Carlo results below test the particle-deposition and photon-transport conditions required to realize that potential.

Table 1. Relative theoretical comparison of the three structures for radioluminescent conversion normalized to unit module volume.

Structure	Relative Source Activity	Ideal Particle Interception Factor	Ideal Light Distribution Factor	Relative Light Output	Relative Light Power Density	Ideal Collection Factor
CS	4	50%	50%	1	0.25	50%
WLC	3	100%	66.7%	2	0.5	66.7%
WLCA	6	100%	100%	6	1	100%

2.2. Material Selection and Spectral Matching

GAGG:Ce was selected as the RL converter because of its high density, effective decay energy deposition, high light yield, transparency, and radiation stability. Its high refractive index enables waveguiding along each column but also increases total internal reflection. Figure 2 presents the emission spectrum of GAGG:Ce and the external quantum efficiency (EQE) curve of the AlGaInP PV cell. The overlap is necessary but not sufficient for high electrical output, which also depends on photon flux and the PV response under low irradiance [10,11].

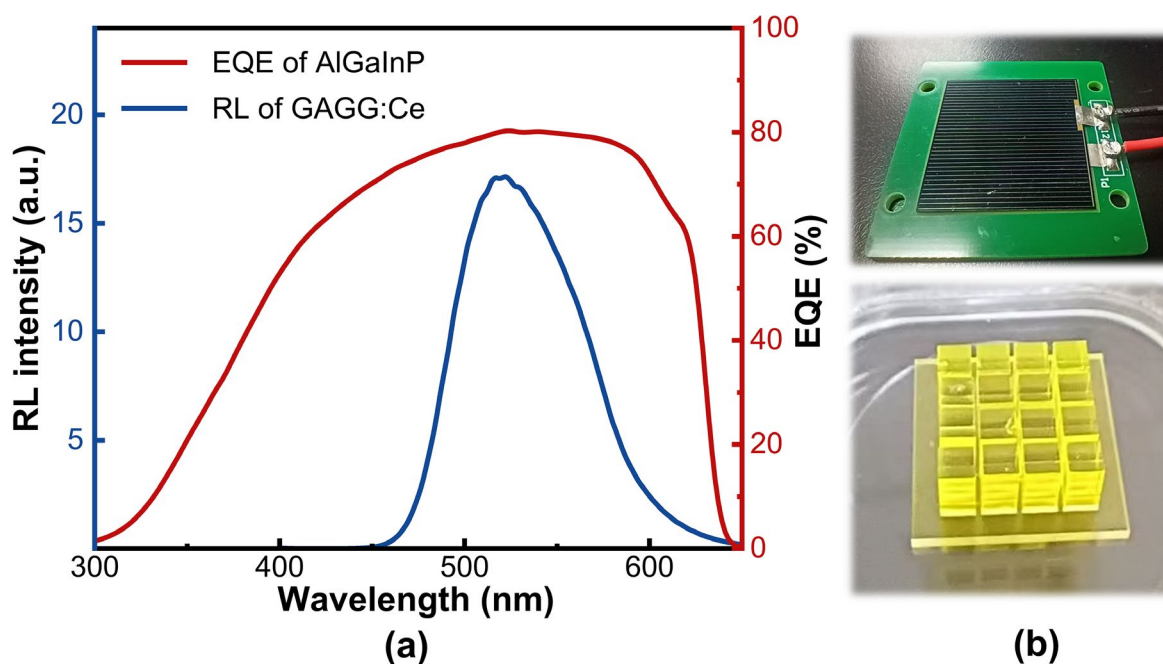


Figure 2. (a) Measured RL spectrum of the GAGG:Ce scintillator and EQE of the AlGaInP photovoltaic cell. (b) Photographs of the AlGaInP PV cell and columnar GAGG:Ce scintillators.

2.3. Monte Carlo Modeling

MCNP5 was used for coupled particle transport and energy deposition, and Geant4 for electron transport, scintillation generation, and optical-photon transport [30]. The MCNP calculations use representative monoenergetic electrons. Geant4 generates scintillation from its own electron transport. The WLCA contains 4×4 columns, each $2 \times 2 \times 5$ mm. Deposition is reported per source electron or as a fraction of initial electron energy. These quantities are distinct from optical collection and electrical conversion efficiency. Material definitions and details of the simulation method are provided in Supplementary S1. The principal outputs were particle emission efficiency, emitted-particle intensity, spatial energy-deposition distributions, source self-absorption, escaped energy, and the energy deposition efficiency in GAGG:Ce. The CS, WLC, and WLCA models used the same source and converter materials so that the observed differences could be attributed primarily to geometry.

3. Results and Discussion

3.1. Optimization of Radiation Source and Scintillator Thickness

Source-region thickness controls two competing quantities: radiation source activity and escape probability. At fixed activity density, the total activity of the radiation source increases approximately in proportion to loading thickness, but the fraction of beta particles that escape the source decreases because decay particles traverse more $\text{Sr}(\text{NO}_3)_2$. As shown in Figure 3a, the particle emission efficiency remains close to 100% below 20 μm , then

decreases continuously to approximately 27% at 250 μm . The emitted-particle intensity is proportional to the product of source activity and escape efficiency. Therefore, it continues to rise even while the efficiency falls and then approaches a self-absorption-limited plateau. At 120 μm , the normalized emitted-particle intensity reaches 99% of its saturation value and the particle emission efficiency is approximately 55.9%. Increasing the thickness beyond 120 μm would add source material but yield little additional outward decay particle intensity, while increasing energy losses due to source self-absorption and module volume. Therefore, 120 μm is selected as the minimum equivalent thickness that effectively reaches saturation.

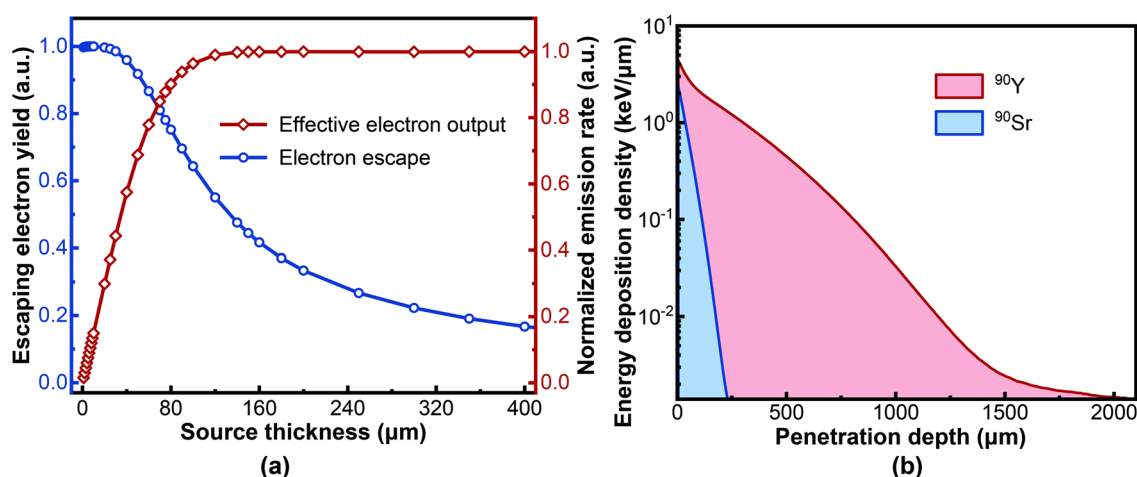


Figure 3. (a) Electron escape efficiency and normalized thickness-weighted electron yield as functions of the ^{90}Sr source layer thickness. (b) Energy deposition density as a function of penetration depth in GAGG:Ce for beta particles emitted by ^{90}Sr and ^{90}Y .

The ^{90}Y , formed after ^{90}Sr beta decay, is also a beta emitter, with weak accompanying gamma emission. Because the ^{90}Y spectrum extends to higher energy than the ^{90}Sr spectrum, the two nuclides set different scintillator-thickness requirements. Figure 3b shows that most of the energy of ^{90}Sr particles is deposited near the GAGG:Ce surface, whereas ^{90}Y particles penetrate more deeply. At 2 mm, the calculated energy deposition efficiencies are 99.9% for ^{90}Sr and 99.6% for ^{90}Y . The energy deposition efficiency of ^{90}Y reaches 99.9% at a thickness of 3.84 mm. At this point, the thickness has increased by 1.84 mm, while the deposited-energy fraction has increased by only approximately 0.3%. The additional crystal would also lengthen the path of RL photons, increasing the probability of bulk absorption, repeated total internal reflection, and leakage before collection. Therefore, it was believed that a 2 mm-thick GAGG:Ce scintillator could absorb almost all the energy. In subsequent simulations, the GAGG:Ce thickness was set to 2 mm.

3.2. Spatial Energy-Deposition Characteristics

Figure 4 shows the energy-deposition fields for the three structures at the crystal thickness of 2 mm and the radiation source thickness of 120 μm . The left-hand figures correspond to excitation by the ^{90}Sr source, and the right-hand figures correspond to excitation by the ^{90}Y source, while each pixel represents a $10 \mu\text{m} \times 10 \mu\text{m}$ region. For all three geometries, ^{90}Sr deposition is strongly localized, with almost all the energy deposited near the surface of the GAGG:Ce scintillator. Meanwhile, at a depth of 2 mm, the energy deposition density decreases by six orders of magnitude. The ^{90}Y field decays more gradually, decreasing by only about one order of magnitude over the first 500 μm . During the decay process, the activities of ^{90}Sr and ^{90}Y approach equality, so the higher beta energy of ^{90}Y makes it a major contributor to the RL. The CS and WLC structures show

similar through-thickness gradients because both retain planar source-phosphor interfaces, while the WLC structure primarily increases the number of useful emission directions. In the WLCA-based RPVC, interior columns are irradiated by four radiation source regions, distributing energy deposition over multiple faces and generating RL closer to several potential collection boundaries.

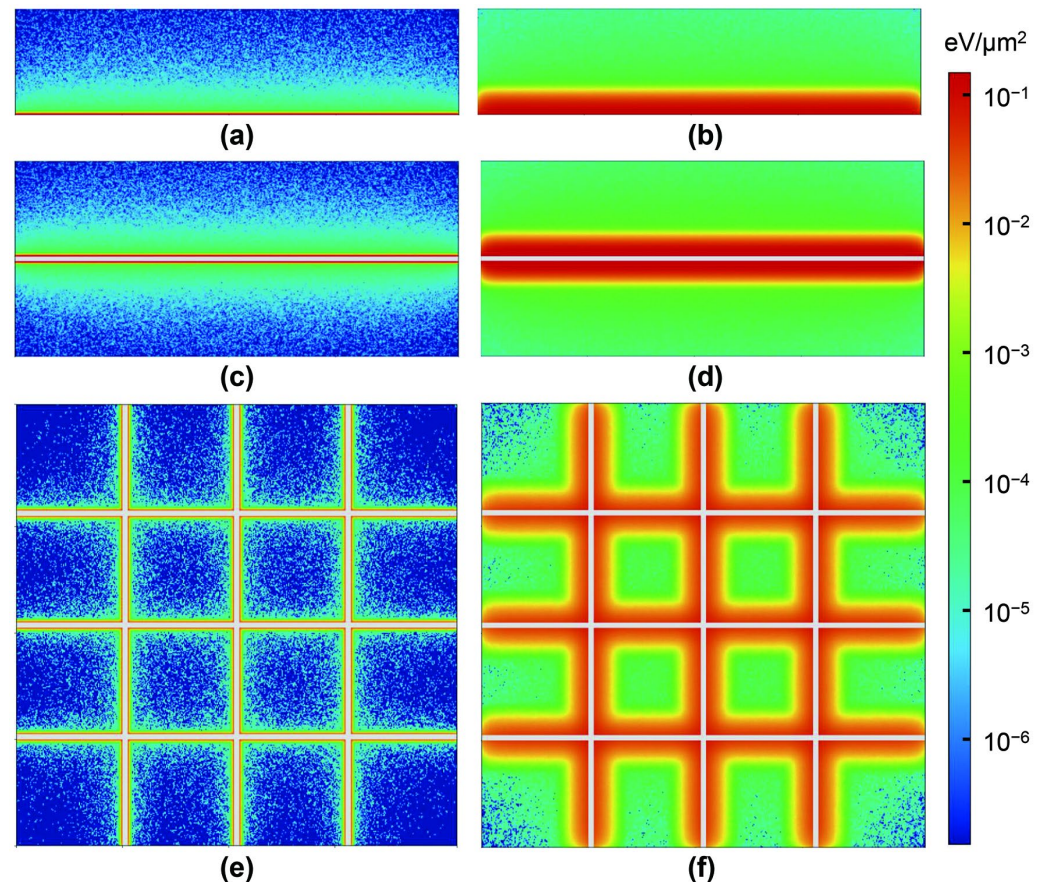


Figure 4. Archived energy-deposition distributions for the CS, WLC and WLCA structures. (a) CS, ^{90}Sr ; (b) CS, ^{90}Y ; (c) WLC, ^{90}Sr ; (d) WLC, ^{90}Y ; (e) WLCA, ^{90}Sr ; and (f) WLCA, ^{90}Y . The planar crystal thickness and array column width are 2 mm.

3.3. Particle and Photon Transport

Figure 5 qualitatively links geometry to representative beta-particle and RL-photon trajectories. In the CS structure (Figure 5a), numerous beta particles leave the radiation source on the side opposite the GAGG:Ce layer, illustrating the unused emission hemisphere. In the WLC structure (Figure 5b), many photons are confined by total internal reflection and guided toward a side surface, although the figure also shows a beta particle escaping from the scintillator. In the WLCA structure (Figure 5c), the tracks of beta particles terminate inside of GAGG:Ce, and the larger source activity produces denser photon trajectories. A substantial number of photons still pass from high-index GAGG:Ce into the surrounding air. Reflective inner encapsulation is necessary to reduce photon leakage from the array, and the coating must minimize the absorption of beta particles and improve edge extraction efficiency [29]. These displays illustrate the conversion process and transport mechanism, but there is still a possibility of some particles escaping. The proposed radioluminescent module is enclosed by a transparent quartz frame intended to attenuate electrons while transmitting RL photons. However, secondary electrons and bremsstrahlung radiation may still irradiate the PV cells. The related study discusses quartz encapsulation and radiation

effects in GAGG:Ce waveguides [27] but does not establish the lifetime of the AlGaInP PV cell. The actual enclosure thickness and PV dose require further assessment in future work.

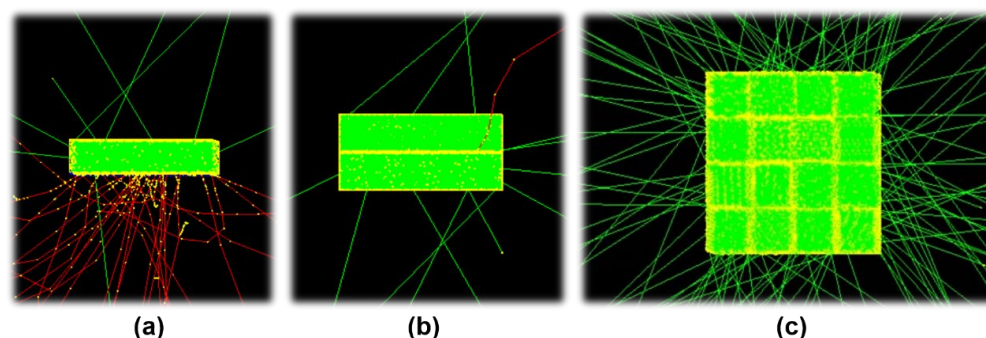


Figure 5. Electron and RL trajectories for the (a) CS, (b) WLC and (c) WLCA structures. Red lines represent electrons, and green lines represent RL photons.

3.4. Regional Energy Partition in the WLCA

Figure 6 resolves the WLCA energy distribution by region. Under ^{90}Sr excitation, a corner scintillator receives approximately 2.6 keV, whereas a central crystal receives approximately 5.2 keV. The factor-of-two difference is caused by coordination: central columns border more source-loading regions, while corner columns have fewer radiation source-facing surfaces. Each $2\text{ mm} \times 120\text{ }\mu\text{m}$ region of the radiation source self-absorbs approximately 5.3 keV. In the complete array, 62.21 keV is deposited in the GAGG:Ce scintillator, corresponding to an energy deposition efficiency of 31.79%; approximately 2.756 keV escapes, and the self-absorption efficiency of the ^{90}Sr source is 66.8%. For ^{90}Y , the ratio of energy deposited in a central column to that deposited in a corner column exceeds two because the more penetrating electrons also excite neighboring GAGG:Ce columns. The beta energy reduces the self-absorption of the radiation source to 15.55% and increases GAGG:Ce deposition to 707.06 keV, corresponding to a proportion of 75.78%. Meanwhile, it also leads to an increase in the fraction of energy escaping the array to 8.67%. The lower-energy electrons emitted by ^{90}Sr lose most of their energy through source self-absorption, whereas the higher-energy electrons emitted by ^{90}Y exhibit greater escape losses at the array boundary. Therefore, the future optimization should combine reflective encapsulation with an outer scintillator guard region.

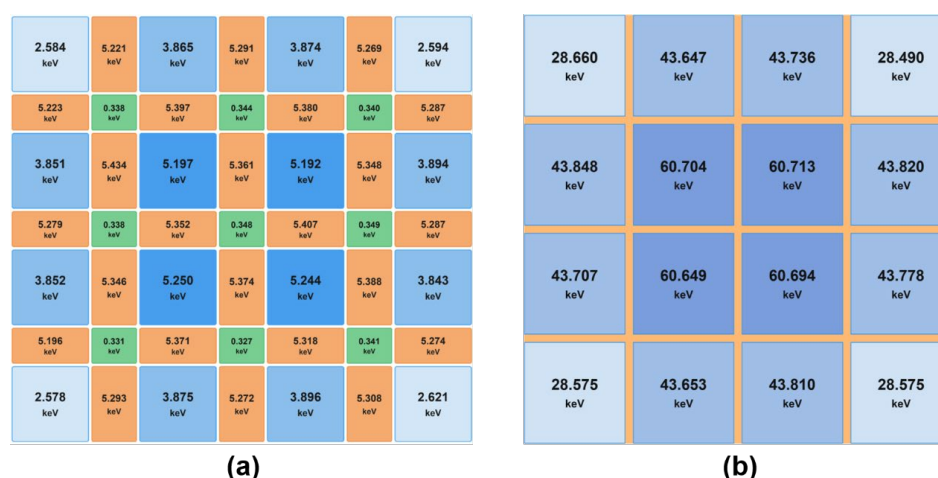


Figure 6. Regional energy deposition in the WLCA structure for representative monoenergetic electrons from (a) ^{90}Sr and (b) ^{90}Y . Blue regions represent GAGG:Ce columns. Orange and green regions represent source-filled gap segments and their intersections, respectively; energy deposition values are shown for both the scintillator and source regions.

4. Conclusions

This study proposed a WLCA structure for ^{90}Sr RPVCs and evaluated the transport and conversion process of decay particles and RL photons through analyses using MCNP and Geant4. At a source thickness of 120 μm , the emitted-electron yield reaches 98.93% of its maximum sampled value, while the electron emission efficiency remains 55.9%. The first 2 mm of GAGG:Ce contains 99.9% and 99.6% of the total deposited energy for ^{90}Sr and ^{90}Y , respectively. In the full-array model, the energy deposition efficiency in the GAGG:Ce scintillator was 31.79% for ^{90}Sr and 75.78% for ^{90}Y , while the corresponding source self-absorption fractions were 66.8% and 15.55%. Relative to the CS and WLC structures, the WLCA enables multidirectional excitation and improved beta-particle confinement. Photon-trajectory analysis indicates that reflective inner encapsulation is required to limit optical leakage. These results define the principal geometric parameters and transport constraints for subsequent fabrication and experimental validation of the WLCA-based RPVC.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/electronics15194580/s1>.

Author Contributions: T.J. was responsible for manuscript conceptualization, methodology, and writing—original draft preparation. Y.L. and C.W. were responsible for supervision and project administration. N.W. was responsible for resource provision and funding acquisition. H.S. was responsible for resource provision, funding acquisition, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Scientific and Technological Research Program of the Chongqing Municipal Education Commission (Grant No. KJQN202603107), the China Postdoctoral Science Foundation (Grant No. 2026M790956), and the National Natural Science Foundation of China (Grant Nos. 12305391 and U2241284).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: No generative AI tools were used to generate simulation data, perform data analysis, create figures, or derive scientific conclusions. During the preparation of this manuscript, the authors used ChatGPT 5.6 (OpenAI) only for language polishing and grammar correction. All AI-assisted content was carefully reviewed and revised by the authors. The authors take full responsibility for the content of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
RPVC	Radio-photovoltaic cell
CS	Conventional sandwich
RL	Radioluminescence
PV	Photovoltaic
EQE	External quantum efficiency
WLC	Waveguide light-concentration
WLCA	Waveguide light-concentration array
MCNP	Monte Carlo N-Particle
GAGG:Ce	Cerium-doped gadolinium aluminum gallium garnet

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