MULTISPECTRAL HARVESTING BY RARE-EARTH BASED NANOPHOSPHORS FOR HIGH-EFFICIENCY TRANSPARENT LUMINESCENT SOLAR CONCENTRATOR

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by

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This thesis is dedicated to my loving and caring mother Ms. Vijay Kataria who will forever be my inspiration and the source of my strength and faith.

CERTIFICATE

This is to certify that the Ph.D. thesis entitled ***"Multispectral harvesting by rare-earth based nanophosphors for high efficiency transparent luminescent solar concentrator"*** is being submitted by **Ms. VANJULA KATARIA** to the Indian Institute of Technology (I.I.T) Delhi in fulfillment for the award of degree **"*Doctor of Philosophy (Ph.D.)*"**. This thesis is a record of the original research work carried out entirely by her under my supervision and guidance. In my opinion, the dissertation has reached the standard of fulfilling the requirements of all the regulations related to the degree. The results contained in this thesis have not been submitted either in part or full, to any other University or Institute for the award of any degree or diploma.

Place- I.I.T Delhi, New Delhi

Date-

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DECLARATION

This is to certify that the research work presented in the thesis entitled ***"Multispectral harvesting by rare-earth based nanophosphors for high efficiency transparent luminescent solar concentrator"*** is being submitted by me in fulfillment as per the requirement for the award of the degree of ***Doctor of Philosophy (Ph.D.)*** at the Indian Institute of Technology (I.I.T) Delhi. This thesis is comprising of only my original research work that has not been published anywhere by anybody else. To the best of my knowledge and belief, this thesis contains no material previously published by any other person or group except where due reference is cited.

Place- I.I.T Delhi, New Delhi

Date-

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ABSTRACT

Over the last few decades, the objective of focussing massive amounts of research efforts to enhance the efficiency limit of single-junction Silicon- solar cells (Si-solar cells) is to push forward the use of renewable energy based on solar technology. The most widely implemented Si-solar cells suffer from a significant drawback of limited capability to utilize the solar spectrum, restricting their energy conversion efficiency. For this, many options, including the use of multi-junction solar cells, layers of spectral converters, solar concentration systems, and others, have been proposed. Solar concentration systems work on the principle of sunlight collection over large areas by concentrating mostly direct sunlight and focusing it onto a compact receiver to increase photon flux density. Traditionally, concentrators worked by tracking the Sun's movement to produce high optical intensities, often employing large mobile lenses and mirrors (Parabolic Lenses, Fresnel Reflectors, etc.) and then concentrating it to a common point. Though the efficiency of solar cells or photovoltaic cells (PV-cells) did increase by these choices, they still suffered from some disadvantages such as enormous costs of deployment, substantial space requirements, and frequent high maintenance for regular running of the devices.

In the decade of 1970s, a luminescent solar concentrator (LSC) was projected as a cost-effective alternative to conventional solar concentration systems. Typical first-generation LSC consisted of a transparent glass or plastic slab dispersed with some luminescent dye molecules, which absorbed high energy incident photons and emitted lower energy photons via Stoke's shift phenomenon. A significant portion of these emitted photons then travels towards the edges of the transparent slab through total internal reflection (TIR) within the LSC, where the coupled PV-cells then collect these photons. Various losses limited the performance of such an LSC, the majority being the self-absorption losses (incurred by the luminophore itself), also called reabsorption losses due to

overlapping absorption (visible regime only) and emission spectral bands. Thus, earlier LSCs were useful in collecting and concentrating the sunlight, but the conversion was minuscule.

Regardless of such a vast system, the PV-cells still couldn't utilize a considerable portion of the full solar spectrum as Si- solar cells have their spectral responsivity maxima limited to the visible region only. Hereon, a more lucrative choice to beat this limit came along by optical conversion of the incoming solar spectrum before it enters the solar cells, which surmounts the losses incurred in the solar cells – thermalization losses and transmission losses. The losses due to thermalization could be reduced by using downconversion (DC) of the incident spectrum, whereby high energy photons are converted or shifted into lower-energy photons. The reduction of transmission losses would require upconversion (UC), whereby a higher energy photon is created by a combination of two or more lower energy photons. Henceforth, the scientific community nowadays is looking forward to new avenues being offered by luminescent nanomaterials that can be used for the collection and trapping of light at near-Infrared (NIR) and ultraviolet (UV) wavelengths also, which constitute a significant fraction of usable solar radiation.

Since the inception of LSC, the predominant area of research in LSC gathering peak attention has been the fluorophore or dye compound utilized for the conversion of light. Primarily this is because of the role that a fluorophore plays in determining the power conversion efficiency and light concentration factor of an LSC. Organic dyes are most famously used to improve LSC performance, but they suffer from very poor photostability, overlapping excitation-emission regions, and narrow absorption band. Some of these disadvantages can be alleviated by engineered quantum dots (QDs), which provide significant quantum efficiency and no emission reabsorption; but suffer from the huge cost of preparation and extremely high toxicity along with low stability. On the other hand, non-heavy metal QDs steer clear of these shortcomings and are non-toxic but offer only Stoke's shift from UV to visible, which still renders the NIR region non-utilized.

Nonetheless, all these luminescent materials degrade under prolonged light exposure and in ambience very soon.

Hence, the performance of an LSC is again falling short that can be overcome by the introduction of new fluorophores, which are photostable, non-toxic, and downconverts, as well as upconverts incoming radiation with coincidental emission band and solar cell's spectral response. The present work outlines the development of lanthanide (Ln^{3+}) or rare-earth (RE) based efficient phosphor materials for spectral modification of UV and NIR regions via DC and UC, respectively, and emission lying in regions overlapping with spectral responsivity maxima of solar cells. Such phosphor materials are non-toxic, highly photostable, don't degrade in ambient conditions, and have high emission intensities while bypassing all the disadvantages mentioned above for organic dyes and QDs.

In the present thesis, the Y_2O_3: Eu^{3+} nanophosphors have been synthesized as downconverters, which offered large Stokes shift of UV (255 nm, 385 nm) and Blue (450 nm, 467 nm) excitation wavelengths emitting a hypersensitive scarlet red emission peak characteristic to Eu^{3+}- ions. The Gd_2O_2S: Er^{3+}, Yb^{3+} nanophosphor offered multispectral excitation profile ranging from UV (285 nm, 380 nm), Blue (450 nm) and NIR (808nm, 980 nm, and 1064 nm) with emission lines in diverse spectral regions (UV, visible and NIR) indicating concurrent Stoke's and anti-Stoke's photoluminescence. Various optical transactions taking place between the dopant ions (Er^{3+}, Yb^{3+}) leading to such multiplexed emissions for UC and DC; and transitions occurring in Eu^{3+}- levels for DC are discussed in detail. The parametric optimization of both nanophosphors across various synthesis factors and an exhaustive experimental study on various structural, morphological, and optical properties of these compounds have been carried.

The synthesized nanophosphors offering DC and UC are then used as a dye in the fabrication of PolyMethyl Meth Acrylate (PMMA) based transparent LSCs via a novel method of Solvation-Gelation-Solidification. Complete optimization encircling many synthesis parameters has been achieved, and LSC slabs with varying nanophosphor dispersion ratios or varying edge width have been fabricated. The calculated electrical parameters (I_{SC}, V_{OC}, P_{MP}) and efficiency parameters (η_{PCE}, $\eta_{OE,}$ and τ_O) of an edge coupled mini solar panel with respect to its bare counterpart of the same size demonstrated high-performance enhancement due to LSC. The impact of edge-veil effect, solvent, and prolonged irradiation on PL behavior is investigated and analyzed for best performance conditions.

सार

पिछले कुछ दशकों में, एकल-जंक्शन सिलिकॉन- सौर कोशिकाओं (Si- सौर कोशिकाओं) की दक्षता सीमा को बढ़ाने के लिए बड़े पैमाने पर अनुसंधान प्रयासों को ध्यान में रखते हुए सौर प्रौद्योगिकी पर आधारित नवीकरणीय ऊर्जा के उपयोग को आगे बढ़ाने का उद्देश्य है। सबसे व्यापक रूप से कार्यान्वित सी-सोलर सेल सौर ऊर्जा स्पेक्ट्रम का उपयोग करने के लिए सीमित क्षमता के एक महत्वपूर्ण दोष से ग्रस्त हैं, उनकी ऊर्जा रूपांतरण दक्षता को सीमित करते हैं। इसके लिए, बहु-जंक्शन सौर कोशिकाओं के उपयोग, स्पेक्ट्रल कन्वर्टर्स की परतों, सौर एकाग्रता प्रणालियों और अन्य सहित कई विकल्प प्रस्तावित किए गए हैं। सौर सांद्रता प्रणाली सूर्य के प्रकाश के संग्रह के सिद्धांत पर काम करती है, जो ज्यादातर प्रत्यक्ष सूर्य के प्रकाश को केंद्रित करके और फोटॉन फ्लक्स घनत्व को बढ़ाने के लिए एक कॉम्पैक्ट रिसीवर पर ध्यान केंद्रित करती है। परंपरागत रूप से, सांद्रक ने उच्च ऑप्टिकल तीव्रता का उत्पादन करने के लिए सूर्य के आंदोलन को ट्रैक करके काम किया, अक्सर बड़े मोबाइल लेंस और दर्पण (पैराबोलिक लेंस, फ्रेसेल रिफ्लेक्टर, आदि) को रोजगार दिया और फिर इसे एक सामान्य बिंदु पर केंद्रित किया। यद्यपि इन विकल्पों से सौर कोशिकाओं या फोटोवोल्टिक कोशिकाओं (PV-cells) की दक्षता में वृद्धि हुई, फिर भी उन्हें कुछ नुकसानों से सामना करना पड़ा, जैसे कि तैनाती की भारी लागत, पर्याप्त स्थान की आवश्यकताएं और उपकरणों के नियमित रूप से चलने के लिए लगातार उच्च रखरखाव।

1970 के दशक में, एक luminescent सौर संकेंद्रक (LSC) को पारंपरिक सौर एकाग्रता प्रणालियों के लिए एक लागत प्रभावी विकल्प के रूप में पेश किया गया था। विशिष्ट प्रथम-पीढ़ी एलएससी में एक पारदर्शी ग्लास या प्लास्टिक स्लैब शामिल होता है, जो कुछ ल्यूमिनेसेंट डाई अणुओं के साथ फैला होता है, जो उच्च ऊर्जा घटना फोटॉनों को अवशोषित करता है और स्टोक की शिफ्ट घटना के माध्यम से कम ऊर्जा फोटॉन उत्सर्जित करता है। इन उत्सर्जित फोटॉनों का एक महत्वपूर्ण हिस्सा तब एलएससी के भीतर कुल आंतरिक प्रतिबिंब (टीआईआर) के माध्यम से पारदर्शी स्लैब के

किनारों की ओर जाता है, जहां युग्मित पीवी-कोशिकाएं फिर इन फोटॉनों को इकट्ठा करती हैं। विभिन्न नुकसानों ने इस तरह के एलएससी के प्रदर्शन को सीमित कर दिया, बहुसंख्यक स्वयं-अवशोषण हानि (स्वयं ल्यूमिनोफोर द्वारा की गई), जिसे अतिव्यापी अवशोषण (केवल दृश्यमान शासन) और उत्सर्जन वर्णक्रमीय बैंड के कारण पुन: अवशोषण नुकसान कहा जाता है। इस प्रकार, पहले एलएससी सूरज की रोशनी को इकट्ठा करने और ध्यान केंद्रित करने में उपयोगी थे, लेकिन रूपांतरण बहुत कम था।

इस तरह की एक विशाल प्रणाली के बावजूद, PV- कोशिकाएं अभी भी पूर्ण सौर स्पेक्ट्रम के एक बड़े हिस्से का उपयोग नहीं कर सकती हैं क्योंकि Si- सौर कोशिकाओं में उनकी वर्णक्रमीय प्रतिक्रियाशीलता अधिकतम दृश्य क्षेत्र तक ही सीमित है। इसके अलावा, इस सीमा को हरा देने के लिए एक अधिक आकर्षक विकल्प आने वाले सौर स्पेक्ट्रम के ऑप्टिकल रूपांतरण के साथ आया, इससे पहले कि यह सौर कोशिकाओं में प्रवेश करता है, जो सौर कोशिकाओं में हुए नुकसानों का आकलन करता है - थर्मलकरण नुकसान और संचरण नुकसान। घटना स्पेक्ट्रम के डाउनकॉनवर्सन (डीसी) का उपयोग करके थर्मलकरण के कारण होने वाले नुकसान को कम किया जा सकता है, जिससे उच्च ऊर्जा फोटॉन को परिवर्तित किया जाता है या निम्न-ऊर्जा फोटॉन में स्थानांतरित किया जाता है। ट्रांसमिशन लॉस में कमी के लिए अपसंवर्धन (यूसी) की आवश्यकता होती है, जिससे एक या अधिक निम्न ऊर्जा वाले फोटॉन के संयोजन से उच्च ऊर्जा फोटॉन का निर्माण होता है। इसके बाद, वैज्ञानिक समुदाय आजकल ल्युमिनसेंट नैनोमेट्रिक्स द्वारा पेश किए जा रहे नए रास्तों का इंतजार कर रहे हैं, जिनका उपयोग निकट-इन्फ्रारेड (एनआईआर) और पराबैंगनी (यूवी) तरंग दैर्ध्य में प्रकाश के संग्रह और जाल के लिए भी किया जा सकता है, जो प्रयोग करने योग्य का एक महत्वपूर्ण हिस्सा है सौर विकिरण।

एलएससी की स्थापना के बाद से, एलएससी के शिखर के ध्यान में अनुसंधान के प्रमुख क्षेत्र प्रकाश के रूपांतरण के लिए उपयोग किए जाने वाले फ्लोरोफोर या डाई कंपाउंड रहे हैं। मुख्य रूप से यह उस भूमिका के कारण है जो एक एलएससी के बिजली रूपांतरण दक्षता और प्रकाश एकाग्रता कारक को निर्धारित करने में एक फ्लोरोफोर निभाता है। कार्बनिक रंगों को सबसे प्रसिद्ध एलएससी प्रदर्शन में सुधार करने के लिए उपयोग किया जाता है, लेकिन वे बहुत खराब फोटोस्टैबिलिटी, अतिव्यापी उत्सर्जन-उत्सर्जन क्षेत्रों और संकीर्ण अवशोषण बैंड से पीड़ित होते हैं। इनमें से कुछ नुकसान को इंजीनियर क्वांटम डॉट्स (QDs) द्वारा कम किया जा सकता है, जो महत्वपूर्ण क्वांटम दक्षता और कोई उत्सर्जन पुनर्संयोजन प्रदान नहीं करता है; लेकिन कम स्थिरता के साथ तैयारी की अत्यधिक लागत और अत्यधिक विषाक्तता से ग्रस्त हैं। दूसरी ओर, गैर-भारी धातु QDs इन कमियों को स्पष्ट करते हैं और गैर विषैले होते हैं, लेकिन यूवी से केवल स्टोक के दृश्यमान होने की पेशकश करते हैं, जो अभी भी निकट-अवरक्त (NIR) क्षेत्र को गैर-उपयोग करता है। बहरहाल, ये सभी ल्यूमिनेसेंट सामग्री बहुत लंबे समय तक प्रकाश के संपर्क में रहती हैं और बहुत जल्द परिवेश में आ जाती हैं।

इसलिए, एलएससी का प्रदर्शन फिर से कम हो रहा है जिसे नए फ़्लोरोफ़ोर्स की शुरूआत से दूर किया जा सकता है, जो कि फोटोस्टेटेबल, गैर-विषैले और डाउनकंवर हैं, साथ ही साथ संयोग उत्सर्जन बैंड और सौर सेल की वर्णक्रमीय प्रतिक्रिया के साथ आने वाले विकिरण को अपकेंद्रित करता है। वर्तमान काम क्रमशः लैंथेनाइड (Ln^{3+}) या दुर्लभ-पृथ्वी (आरई) आधारित कुशल फास्फोर सामग्री के विकास के लिए यूवी और एनआईआर क्षेत्रों के डीसी और यूसी के माध्यम से वर्णक्रमीय संशोधन के आधार पर क्रमशः, और उत्सर्जन उत्सर्जन क्षेत्रों में झूठ बोल रही है जो सौर कोशिकाओं की वर्णक्रमीय प्रतिक्रियाशीलता से अधिक है । इस तरह के फॉस्फोर पदार्थ गैर विषैले, अत्यधिक फोटोस्टेबल होते हैं, जो परिवेश की स्थितियों में गिरावट नहीं करते हैं, और कार्बनिक रंगों और क्यूडी के लिए ऊपर उल्लिखित सभी नुकसानों को दरकिनार करते हुए उच्च उत्सर्जन तीव्रता है।

वर्तमान थीसिस में, Y_2O_3: Eu^{3+} नैनोफॉस्फोरस को डाउनकोवर्टर के रूप में संश्लेषित किया गया है, जिसने यूवी (255 एनएम, 385 एनएम) और ब्लू (450 एनएम, 4 एनएम) के बड़े स्टोक की उत्तेजना की पेशकश की, जो हाइपरसेंसिटिव स्कार्लेट लाल उत्सर्जन चोटी की विशेषता है। Eu^{3+} - आयन। Gd_2O_2S: Er^{3+}, Yb^{3+} नैनोफॉस्फोर ने मल्टीस्पेक्ट्रल उत्तेजना प्रोफ़ाइल यूवी (285 एनएम, 380 एनएम), ब्लू (450 एनएम) और NIR (808nm, 980 एनएम, और 1064 एनएम) से लेकर विभिन्न वर्णक्रमीय क्षेत्रों (यूवी, दृश्यमान) में उत्सर्जन लाइनों के साथ पेश की। और एनआईआर) समवर्ती स्टोक और एंटी-स्टोक की फोटोलुमिनेसेंस का संकेत देता है। डोपेंट आयनों (Er^{3+}, Yb^{3+}) के बीच होने वाले विभिन्न ऑप्टिकल लेन-देन, ऐसे मल्टीप्लेक्स उत्सर्जन और Eu^{3+} में होने वाले संक्रमणों के लिए अग्रणी होते हैं - स्तरों पर विस्तार से चर्चा की जाती है। विभिन्न संश्लेषण कारकों और विभिन्न संरचनात्मक, आकारिकी, और इन यौगिकों के ऑप्टिकल गुणों पर एक संपूर्ण प्रयोगात्मक अध्ययन दोनों नैनोफॉस्फोरस के पैरामीट्रिक अनुकूलन किया गया है।

डीसी और यूसी की पेशकश करने वाले संश्लेषित नैनोफॉस्फोरस को तब पॉलीमेथाइल मेथ एक्रिलेट (पीएमएमए) आधारित पारदर्शी एलएससी के निर्माण में डाई के रूप में एक उपन्यास विधि - सॉल्वैशन-जेलेशन-सॉलिडिफिकेशन के माध्यम से उपयोग किया जाता है। कई संश्लेषण मापदंडों को घेरने वाला पूर्ण अनुकूलन हासिल किया गया है, और अलग-अलग नैनोफॉस्फर फैलाव अनुपात या अलग-अलग किनारे की चौड़ाई के साथ एलएससी स्लैब गढ़े गए हैं। गणना की गई बिजली के मापदंडों (I_{SC}, V_{OC}, P_{MP}) और दक्षता मापदंडों (η_{PCE}, η_{OE} और τ_O) के साथ एक युग्मित सौर सेल के नंगे सौर सेल के संबंध में एलएससी के कारण उच्च प्रदर्शन वृद्धि का प्रदर्शन किया। । पीएल व्यवहार पर बढ़त-घूंघट प्रभाव, विलायक और लंबे समय तक विकिरण के प्रभाव की जांच की जाती है और सर्वोत्तम प्रदर्शन स्थितियों के लिए इसका विश्लेषण किया जाता है।

LIST OF PUBLICATIONS

1. **V. Kataria, S. Dixit and D.S Mehta**, "*Investigations on the up/downconversion of Gd_2O_2S: Er, Yb nanophosphor with both excitation wavelength and Yb^{3+}- dependent emission colour modulation*", Journal of Material Science 54 (2019) 13635-50. **I.F: 4.220**

2. **V. Kataria and D.S Mehta**, "*Multispectral harvesting rare-earth oxysulphide based highly efficient transparent luminescent solar concentrator*", Journal of Rare Earths, https://doi.org/10.1016/j.jre.2020.09.021. **I.F: 3.712**

3. **V. Kataria and D.S Mehta**, "*Impact of firing temperature on multi-wavelength selective Stoke's and anti-Stoke's luminescent behaviour by Gd_2O_2S: Er, Yb phosphor and its application in solar energy harvesting*", Journal of Physics D: Applied Physics 51 (2018) 145501. **I.F: 3.207**

4. **V. Kataria and D.S Mehta**, "*Investigation of concurrent emissions in visible, UV and NIR region in Gd_2O_2S: Er, Yb nanophosphor by diverse excitation wavelengths as a function of firing temperature*", Optical Materials 95 (2019) 109204. **I.F: 3.080**

5. **V. Kataria and D.S Mehta**, "*Shape engineered Y_2O_3: Eu^{3+} nanodots for Stoke's shifting high-efficiency PMMA based transparent luminescent solar concentrator*". (Communicated)

<u>International Conferences</u>

1. **V. Kataria and D.S Mehta**, "*Spectroscopic investigation of photoluminescence in X_2O_3/X_2O_2S: Z (X= Gd/Y, Z = Eu/Er/Yb) phosphor via UV and NIR excitation wavelengths: Influence of host-lattice, sintering cycle and varying dopants"*, International Conference on

Optics and Eectro-Optics: ICOL-2019, held at IRDE Dehradun, India.

2. **V. Kataria and D.S Mehta**, "*Upconversion and downconversion in Gd_2O_2S: Er, Yb phosphor for enhanced sunlight harvesting: Effect of firing temperature on multi-mode photoluminescence",* PHOTONICS-2018, held at IIT Delhi, India.

<u>UNDER PREPARATION</u> - (not included in thesis)

1. **V. Kataria, S. Tayal and D.S Mehta**, "*Stimulated emission luminescent solar concentrator embedded with Gd_2O_2S:Er, Yb nanorods for diverse NIR wavelengths sensitized high stimulated optical gain*".

2. **V. Kataria, V. Singh and D.S Mehta**, "*Investigations of stimulated emission gain via white light generating Ce:YAG doped PMMA based light concentrator slab for multiple signal wavelengths*".

3. **V. Kataria, S. Tayal and D.S Mehta**, "*Impact of TiO_2 nanoparticles co-dispersed with blue light and NIR light harvesting nanophosphors on the optical gain under different seed wavelengths*".

4. **V. Kataria and D.S Mehta,** "*Ultraviolet and blue light harvesting dual phosphor co-doped with scattering nanoparticles fluorescent light concentrator for increased response of solar cells*"**.**

5. **V. Kataria and D.S Mehta,** "*Blue light excitable Ce:YAG doped luminescent solar concentrator for enhanced photovoltaic response and lighting applications".*

ABBREVIATIONS & SYMBOLS USED

a……..……..……..……..Crystal lattice Constant in x-axis direction

A…..……..……..……System constant for a combination of flux and crystal

AC-SG……..……..……..……..……Acid-Catalyzed Sol Gel

A_{Edge}……..……..……..……Surface Area of concentrator's edge

AM1.5G……..……..……..……..……Air Mass 1.5 Global

A_{Top}……..……..……..……Surface Area of concentrator's top

b……..……..……..……..Crystal lattice Constant in y-axis direction

BET……..……..……..……..……..…..Back Energy Transfer

BIPV……..……..……..……... Building Integrated Photovoltaic

BSE……..……..……..……..……Backscattered Electrons

c……..……..……..……..Crystal lattice Constant in z-axis direction

C……..……..……..……..……..Concentration Factor

CdS…..……..……..……..……..……....Cadmium Sulfide

CdSe…..……..……..……..……..……....Cadmium Selenide

CdTe…..……..……..……..……..……....Cadmium Telluride

CdZnS…..……..……..……..……..……Cadmium Zinc Sulfide

CET……..……..……..……..……Cooperative Energy Transfer

CIE……..……..……..……..Commission Internationale de l'Eclairage

CL……..……..……..……..……..Cooperative Luminescence

CPC……..……Compound Parabolic Concentrator

CR……..……..……..……..……Cross-Relaxation

CS……..……..……..……..……Cooperative Sensitization

CsPb(BrI)…..……..……..……..Mixed halide perovskite

CuInS……..……..……..…….....Copper Indium Sulfide

CuInSe……..……..……..……..…….....Copper Indium Selenide

CuInSeS……..……..……..……..……...Copper Indium Selenide Sulfide

$C_6H_8O_3.H_2O$……..……..……..……..……..……Citrate Monohydrate

d……..……..……..……..……..Spacing between two parallel crystal planes

D…..……..……..……..……..Crystallite diameter

DC……..……..……..……..……..……... Downconversion

DPBT……..……2-(N, N diethylaniline-4-yl)-4, 6-bis(3,5-dimethylpyrazole-1-yl)-1,3,5-triazine

DPEPO……..……..……..……bis(2-(diphenylphosphino)phenyl) ether oxide

EDX……..……..……..……..……. Energy Dispersive X-Ray

EP……..……..……..……..……..……Energy Pathway

Er_2O_3……..……..……..……..……...Erbium Oxide

ESA……..……..……..……..……....……Excited State Absorption

ET……..……..……..……..……..……..…….....Energy Transfer

ETU……..……..……..……..Energy Transfer Upconversion

Eu_2O_3……..……..……..……..……..Europium Oxide

eV……..……..……..……Electron-Volt

KeV……..……..……..……Kilo Electron-Volt

FF…..……..……..……Fill-Factor

FWHM…..……..……..……...…Full width at half maxima at peak's position

G…..……..……..……..……..……Geometric Gain

Gd_2O_3……..……..……..……..……..Gadolinium Oxide

Gd_2O_2S……..……..……..……..……...Gadolinium Oxysulphide

GOS……..……..……..……Gadolinium Oxysulphide nanophosphor

GSA……..……..……..……..……Ground State Absorption

hfac……..……..……..……..……hexafluoroacetylacetonate

HNO_3……..……..……..……..……..……Nitric Acid

HRTEM……..……..…….... High-Resolution Transmission Electron Microscope

I_{em}……..……..……..……..……..Emission Intensity

I_{LSC}……..……..……Short-circuit Current from concentrator's edge coupled solar cell

I_{MP}……..……..……..……..……Current at Maximum Point

InP…..……..……..……..……..Indium Phosphide

IR……..……..……..……..……..……..……. Infrared

I_{SC}……..……..……..……..……Short-circuit Current

I-V……..……..……..……..…….Current-Voltage

k……..……..……..……..……..…….Boltzmann's Constant

K……..……..……..…….Surface normal to waveguide

K_3PO_4……..……..……..……..……..……Tribasic Pottasium Phosphate

LDS……..……..……..……..……Luminescent Down-shifting

LSC……..……..……..……..……..Luminescent Solar Concentrator

Ln^{3+}……..……..……..……..……..……...…Lanthanide

m%……..……..……..……..……..……mole%

MPA……..……..……..……..……. Multi-Photon Absorption

MPaSSE……..……..……..…….Multi-Phonon anti-Stoke's Sideband Excitation

MPE……..……..……..……..……...Multi-Photon Excitation

n……..……..……..……..…… Number of Pumping Photons

n_1……..……..……..……...Refractive index of waveguide

n_2……..……..……..……...Refractive index of air

Na_2CO_3……..……..……..……..……Sodium Carbonate

NIR……..……..……..……..……..……... Near-Infrared

NIR-QC……..……..……..……..……Near-Infrared Quantum Cutting

OS……..……..……..……..……..Oxysulphide

PAET……..……..……..……..…… Phonon Assisted Energy Transfer

PA-UC……..……..……..…….Photon-Avalanche Upconversion

PbS…..……..……..……..……..……..……..Lead Sulfide

PbSe…..……..……..……..……..……..……..Lead Selenide

PDF……...……..……..……..……..……Powder Diffraction File

PDMS……..……....……..……..……..…….....Poly-DiMethyl Siloxane

P_{In}……..……..……..……..……... Laser's Incident Power

P_{IN}……..……..……..……Incident radiant Power Density

PL……..……..……..……..……..……Photoluminescence

PMMA……..……..……..……..……...Poly-Methyl meth Acrylate

P_{MP}……..……..……..……..……..Maximum Power Point

PMT……..……..……..……..……. Photo-Multiplier Tube

PV……..……..……..……..……..……..…..…Photovoltaic

P-V……...……..……..……..……...…Power-Voltage

QC……...……..……..……..……..……...Quantum Cutting

QD……..……..……..……..……..……..….. Quantum Dot

QY……..……..……..……..……..……Quantum Yield

RE……..……..……..……..……..……..Rare-Earth

RE-OS……..……..……..……..……..Rare-Earth Oxysulphide

RET……..……..……..……..……. Resonant Energy Transfer

RG……...……..……..……..……...Red-Green

SE……...……..……..……..……Secondary Electrons

SEM……..……..……..……..……..…....Scanning Electron Microscope

SHG……..……..……..……..……...Second Harmonic Generation

Si……..……..……..……..……Silicon

SSFF……..……..……..……..……Solid-State Flux Fusion

SSR……..……..……..……..……..…….Solid-State Reaction

STC……..……..……..……..……..Standard testing Conditions

SQ……..……..……..……..……..……..……Shockley-Queisser

t……..……..……..……..……..……Firing time

T……..……..……..……..……..……..Firing temperature

TEM……..……..……..……..……Transmission Electron Microscope

THF……..……..……..……..……...Tetrahydrofuran

TIR……..……..……..……..……..……Total Internal Reflection

TPPO……..……..……..……..……...Triphenyl phosphine oxide

TTA……..……..……..……..……thenoyltrifluoro-acetonate

TW……..……..……..……..……..……TeraWatt

UC……..……..……..……..……..…… Upconversion

UV……..……..……..……..……..……..….... Ultraviolet

UVA……..……..……..……..……..……..UV rays from 320 nm to 400 nm

V_{MP}……..……..……..……..……...Voltage at Maximum Point

V_{OC}……..……..……..……..……..……..Open-circuit Voltage

XRD……..……..……..……..……..……X-Ray Diffraction

Y_2O_3……..……..……..……..……..……...Yttrium Oxide

Yb_2O_3……..……..……..……..……..……Ytterbium Oxide

YO……..……..……..……..……..……Yttrium Oxide nanophosphor

ZnO…..……..……..……..……..……..……..Zinc Oxide

ZnS…..……..……..……..……..……..……..Zinc Sulfide

α……..……..……..……..……Angle between lattice constants b and c

β……..……..……..……..……..Angle between lattice constants a and c

β_W…..……..……..……..……..……FWHM

ΔE…..……..……..……Activation energy including Gibb's free energy and diffusion energy

γ……..……..……..……..Angle between lattice constants a and b

η_{OE}……..……..……..……..……...Optical Efficiency

η_{PCE}……..……..……..……..……Power Conversion Efficiency

θ……..……..……..Angle between incident X-rays and atomic plane

θ_c……..……..……..……Acceptance half-angle

θ_C……..……..……..……Critical Angle

θ_{esc}……..……..……..……...Angle of escape cone

τ ……..……..……..……..……Flux Gain

τ_O……..……..……..……..……..Optical Flux Gain

ϕ……..……..……..……..……..…….Fractions of lost photons

ϕ_{PS}……..……..……..……..……..……Particle growth parameter

λ_P……..……..……..……..Absorption spectrum

λ_S……..……..……..…….Emission spectrum

λ_X……..……..……..……Wavelength of incident X-rays

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