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Full paper

Evolutionary trend analysis of nanogenerator research based on a novel perspective of phased bibliographic coupling

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ABSTRACT

To evaluate the rapid growth of research on nanogenerators and the emergence of promising applications related to nanogenerators, evolutionary trends in the relevant research are analyzed based on phased bibliographic coupling (PBC). Through the novel method of PBC, the evolutionary trend of the relevant research on nanogenerators is roughly categorized into three phases, and the characteristic research topics, issues, articles and terms are discriminated and visualized. Beyond the traditional literature review of domain experts on nanotechnology, this article provides a novel means of visualizing more information about the evolution of the nanogenerator research over the past ten years, based on a more quantitative approach.

1. Introduction

Along with the development of emerging technologies and products such as the Internet of Things (IoT), smart wearable devices (SWD), and clean and renewable energy, increasingly smaller sensors and electronic components, with broad applications, are becoming necessary. The power systems of most smart terminals still depend on the traditional chemical battery, which carries risks to the environment and to health. On the other hand, the traditional chemical battery is limited not only by the lifecycle and the need for frequent recharging but also the manufacturing scale; i.e., the traditional chemical battery cannot be manufactured at the nano or even micro scales to support the use of common electronic devices. Moreover, enhancing the performance of wind and solar energy also confronts challenges to the existing framework of power delivery.

At the same time, emerging nanogenerator technology presents a promising application in areas such as self-powered systems, mechanical or thermal energy harvesting and SWD [1,2]. Although the concept of the "nanogenerator" was first mentioned in 1997 [3], the basic connotation of "nanogenerator" is very similar with nanomotor before 2006. Actually, the phase of "nanogenerator" appeared in several articles before 2006 was to describe a phenomenon of using alternating magnetic field to drive the motion of nanoparticles, which should be more precisely called "nanomotor". The nanogenerator to be presented in this article is about a device that can convert mechanical energy directly into electricity without using magnets and coils [1,2].

Basically, the complete definition and concrete entity on nanogenerator rely on the invention and introduction of piezoelectric nanogenerator (PENG) in 2006 [4], and then studies on nanogenerators have increased after 2006. Fig. 1 depicts the rising trend (time series) of relevant publications on nanogenerators in the Web of Science (WOS) database between 2006 and 2015 through the basic topic search.

Based on Fig. 1, one might conclude that the number of relevant publications on nanogenerators increased rapidly since 2009. However, a non-linear simulation of the time series data reveals that the growth pattern in Fig. 1 is very close to the logistic or exponential function. The simulation result is shown in Fig. 2 and Table 1.

Based on Fig. 2, the logistic regression appears to be the best fitting curve, to which the exponential fitting result is very close. The statistical indicators in Fig. 2 are shown in Table 1.

As nanogenerators are among the most promising and emerging applications of nanotechnology, the increase in research articles on nanogenerators has greatly outpaced the increase in total publications on nanotechnology. Therefore, in what follows, bibliometric analyses are utilized to explore the hidden patterns and reasons for this growth. Potential implications are then presented.

After PENG was pioneered by the academic team of Professor Wang at the Georgia Institute of Technology [4–6], follow-up research grew at a relatively modest and stable rate until the triboelectric nanogenerator (TENG) was proposed in 2012 [7–9]. In the meantime, another type of nanogenerator, the pyroelectric nanogenerator (PRNG), was invented and introduced in formal publications [10]. In the past two

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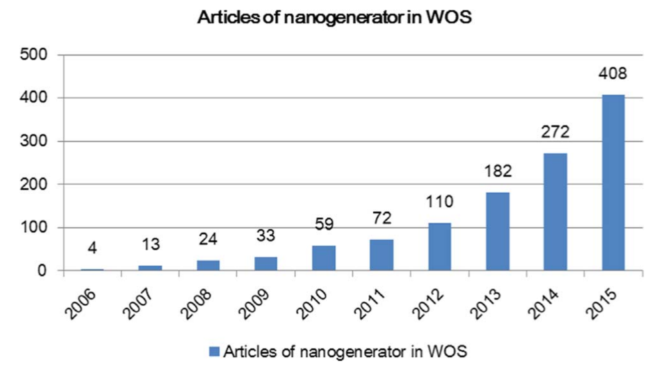

Fig. 1. Time sequence of relevant articles on nanogenerators in WOS.

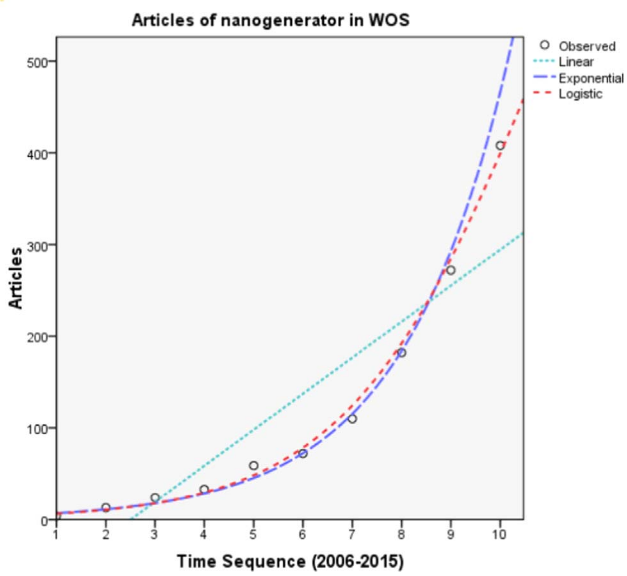

Fig. 2. Fitting the growth curve of the publications on nanogenerators in WOS (2006–2015).

Table 1
Statistical tests of the regression analyses in Fig. 2.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	F-value	Sig.
Linear	0.899	**0.808**	0.784	**61.535**	**33.635**	0.000
Exponential	0.985	**0.971**	0.967	**0.261**	**263.209**	0.000
Logistic (upper bound=1000)	0.990	**0.980**	0.977	**0.238**	**383.349**	0.000

years, the number of relevant publications on nanogenerators has exceeded the total number of such publications in prior years, as more and more branches of science and technology have become integrated into the study of nanogenerators; therefore, bibliometric analyses of the relevant literature on nanogenerators can facilitate knowledge diffusion and interaction between different fields and among interdisciplinary and newer researchers. In addition to a traditional review of literature by domain experts, a bibliometric analysis can reveal another facet of the research fronts on nanogenerators by micro and quantitative means.

2. Data collection and analytical methods

Because the first article on PENG published in 2006 was taken into a milestone of nanogenerators development. Therefore, the timespan for the retrieval of experiments is from 2006 to 2015. At the same time, in view of the different types of literature that are relevant (articles, proceedings, reviews and book chapters, etc.) and the degree of completeness of the metadata in WOS, the article data are selected to be the object of bibliometric analysis. The retrieval experiments are shown in Table 2.

Based on the retrieval results in Table 2, some interesting phenomena can be partially presented. First, although PRNG and TENG were both proposed in 2012, the relevant research on TENG displays much faster growth than that on PENG. Second, some literature discusses at least two of the three types of nanogenerators (PENG, TENG and PRNG), and nine articles cover all of them. Third, among the 1179 articles on nanogenerators, 232 (approximately 20%) appear not to explicitly mention PENG, TENG or PRNG, at least in their titles, abstracts or keywords; some of them focus on issues such as nanogenerators' material [11–13], improving the structure of nanogenerators [14,15], sorts of applications in tumor therapy [16], self-powered systems or sensors [17–19], methods of enhancing energy harvesting [20], and wearable devices and human motion monitoring [21].

In general, bibliometric analyses focused on specific topics are often utilized to provide observations supplementary to domain experts' reviews and comments through more objective and quantitative means. Bibliographic coupling analysis (BCA) can enable exploration of the hidden relationships among articles and partly present the evolutionary pattern of the research frontiers in a specific topic [22]. In contrast to traditional references co-citation, the networking nodes in BCA are articles that are identified using co-citing clustering methods. Relationships among different research topics and articles can then be analyzed and visualized.

Additionally, considering the growth trend of publications presented in Fig. 1 and the times of introduction of the three typical nanogenerators, PENG, TENG and PRNG, the evolutionary phases of nanogenerator research are hypothesized to be divided into three phases:

i) The first phase (2006–2011): the first nanogenerator, PENG, is explored and introduced.
ii) The second phase (2012–2013): two new nanogenerators, TENG and PRNG, are invented and introduced.
iii) The third phase (2014–2015): the applications of nanogenerators are explored and extended.

Undoubtedly, this phase division may be controversial; **however, it is a hypothesis, and the following bibliometric analyses and literature review may support or overthrow it.** In fact, the reasoning process employed is expected to be more significant than the exact phasing and valuable for exploring the evolutionary trend of the relevant research on nanogenerators through a novel perspective and integrated means.

3. Highly cited articles and highly frequent terms in three phases

Frequently cited articles and common terms are often utilized in part to indicate the most popular or mainstream issues within a specific topic of research. If the phase is not considered, the top-cited articles are located in the early stage, based on the generalized pattern of citation, and citation growth over the years or other complementary methods should facilitate this analysis. Here, based on the proposed phases of the development of nanogenerator research, the diversified results of citation frequency analysis are shown in Table 3.

With regard to the information presented in Table 3, more details

Table 2
Retrieval experiments with different rules based on the database of WOS (2006–2015).

No	Retrieval Rule	Result
1#	(TS=("nanogenerator*")) AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	1179
2#	(TS=("piezoelectric*" AND "nanogenerator*")) AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	657
3#	(TS=("triboelectric*" AND "nanogenerator*") OR TS=(TENG AND nanogenerator*)) AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	336
4#	(TS=("pyroelectri*" AND "nanogenerator*")) AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	45
5#	(TS=("triboelectric*" AND "piezoelectric*") AND TS="nanogenerator*") AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	60
6#	(TS=("pyroelectri*" AND "piezoelectric*") AND TS="nanogenerator*") AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	20
7#	(TS=("pyroelectri*" AND "triboelectric*") AND TS="nanogenerator*") AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	18
8#	(TS=("triboelectric*" AND "piezoelectric*" AND "pyroelectri*") AND TS="nanogenerator*") AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2006–2015	9
9#	(TS=nanogenerator* NOT TS=(triboelectric* OR piezoelectric* OR pyroelectri*)) AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A & HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1997–2015	232

could be interpreted. For example, while the article proposing the PENG in *Science* is the most-often cited article, issues relating to the direct-current structure of nanogenerators, new functional materials for nanowires, self-powered nanowire devices, etc., are also very hot topics in the first phase; however, in the second phase, issues related to TENG dominate the citations. Interestingly, in the third phase, all three types of nanogenerators became popular issues. In particular, issues related to PRNG are addressed in the top 5 articles ordered by citation, and wearable devices appears to have been the dominant topic among emerging applications of nanogenerators over the past two years. On the other hand, based on Table 3, differences between the three phases seem significant, which could partly support the reasonableness of this division of phases.

To further explore possible differences between the three phases, co-occurrence frequency analysis of the terms is utilized to partly depict the differences between and connections among the different stages. The analytical tool used is the popular bibliometric software, *CiteSpace* [23]. The scope of term detection encompasses such items as *title, abstract*, *author, keywords*. The results are shown in Fig. 3.

In Fig. 3, although the 10 most frequent terms are presented for each phase, the differences between and connections among the three phases appear to be somewhat significant. Overall, the frequency of co-occurrence increases with publication growth over the years, and most terms overlap during the three phases; however, the order of a given term in different phases shows significant differences, a finding that makes sense. For example, the frequencies of the 3 most frequent terms ("*ZnO nanowires*", "*piezoelectric nanogenerator*" and "*piezoelectric potential*") in phase I continuously decline; however, "*output voltage*" and "*mechanical energy*" maintain nearly persistent growth in the following stages. Compared with the first phase, "*triboelectric nanogenerator*", "*open-circuit voltage*" and "*self-powered system*" first occur in the top 10 most frequent terms, and in the third phase, there are also two new terms in the top 10: "*out power*" and "*room temperature*". One of the emerging nanogenerators, pyroelectric nanogenerator (PRNG), does not enter into the top 10 terms in any of the phases. The results are matched with the retrieval results from the experiments of 6#, 7# and

Table 3
Top 5 most cited articles in the three phases (**citations are computed at 8th Jan., 2017**).

Phase	Citations	Year	Article
I	3229	2006	Wang ZL., Song J. (2006). Piezoelectric nanogenerators based on zinc oxide nanowire arrays. **Science**, 312(5771), 242–246.
	1265	2007	Wang X., Song J., Liu J., Wang ZL. (2007). Direct-current nanogenerator driven by ultrasonic waves. **Science**, 316(5821), 102–105.
	823	2008	Qin Y., Wang X., Wang ZL. (2008). Microfibre–nanowire hybrid structure for energy scavenging. **Nature**, 451(7180), 809–813.
	729	2007	Lieber CM., Wang ZL. (2007). Functional nanowires. **MRS bulletin**, 32(02), 99–108.
	675	2010	Xu S., Qin Y., Xu C., Wei Y., Yang R., Wang ZL. (2010). Self-powered nanowire devices. **Nature nanotechnology**, 5(5), 366–373.
II	436	2012	Fan FR., Tian ZQ., Wang ZL. (2012). Flexible triboelectric generator. **Nano energy**, 1(2), 328–334.
	315	2012	Fan FR., Lin L., Zhu G., Wu W., Zhang R., Wang ZL. (2012). Transparent triboelectric nanogenerators and self-powered pressure sensors based on micropatterned plastic films. **Nano letters**, 12(6), 3109–3114.
	265	2012	Wang S., Lin L., Wang ZL. (2012). Nanoscale triboelectric-effect-enabled energy conversion for sustainably powering portable electronics. **Nano letters**, 12(12), 6339–6346.
	228	2013	Zhu G., Lin ZH., Jing Q., Bai P., Pan C., Yang Y., Wang ZL. (2013). Toward large-scale energy harvesting by a nanoparticle-enhanced triboelectric nanogenerator. **Nano letters**, 13(2), 847–853.
	202	2012	Zhu G., Pan C., Guo W., Chen CY., Zhou Y., Yu R., Wang, ZL. (2012). Triboelectric-generator-driven pulse electrodeposition for micropatterning. **Nano letters**, 12(9), 4960–4965.
III	155	2014	Zhu G., Chen J., Zhang T., Jing Q., Wang ZL. (2014). Radial-arrayed rotary electrification for high performance triboelectric generator. **Nature communications**, 5.
	152	2014	Gong S., Schwalb W., Wang Y., et al. (2014). A wearable and highly sensitive pressure sensor with ultrathin gold nanowires. **Nature communications**, 5.
	111	2014	Dagdeviren C., Yang BD., Su Y., et al. (2014). Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm. **Proceedings of the National Academy of Sciences**, 111(5), 1927–1932.
	101	2014	Zhong J., Zhang Y., Zhong Q., et al. (2014). Fiber-based generator for wearable electronics and mobile medication. **ACS nano**, 8(6), 6273–6280.
	91	2014	Lee JH., Lee KY., Gupta MK., et al. (2014). Highly stretchable piezoelectric-pyroelectric hybrid nanogenerator. **Advanced Materials**, 26(5), 765–769.

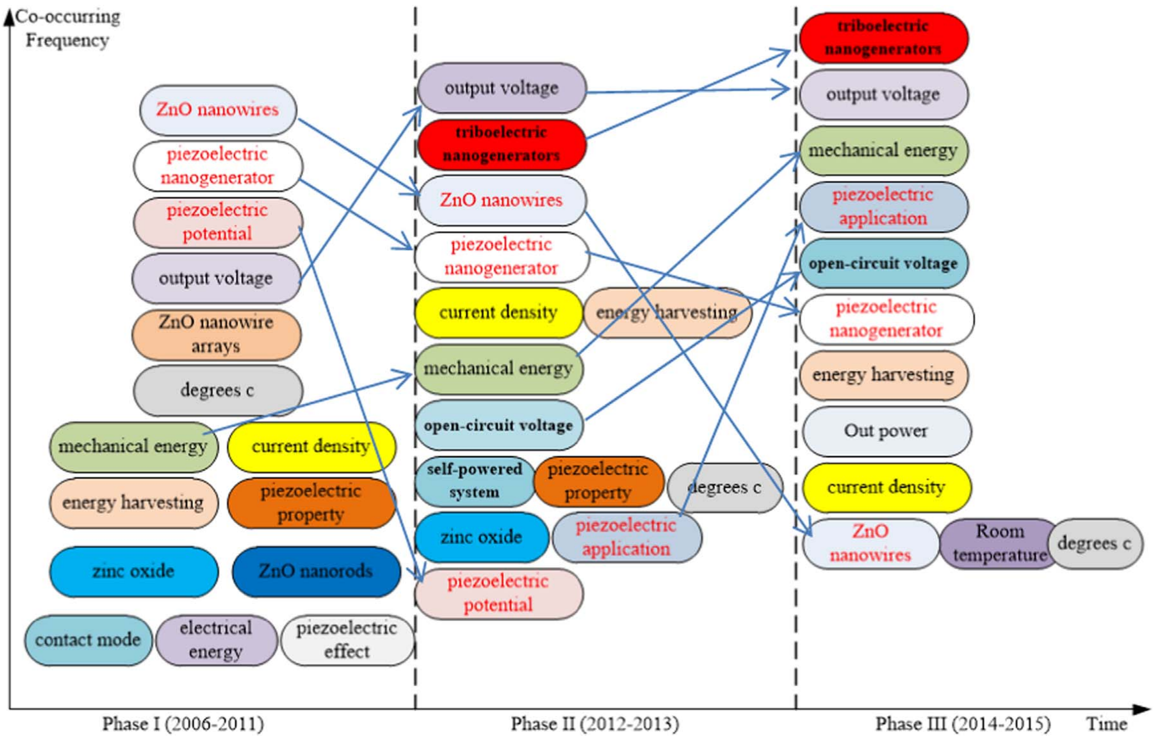

Fig. 3. Top 10 terms with highest frequency of co-occurrence in three phases.

8# presented in Table 2. In fact, the results shown in Fig. 3 depend only on the simple calculation of co-occurrence frequency without any complicated algorithm. Then, the slight differences between the three phases can be observed to be significant to some degree.

4. Analyses of phased bibliographic coupling

In the above, the information presented in Table 3 and Fig. 3 may depict one or two facets of the evolutionary trend of the relevant research on nanogenerators, but cannot reflect the development or evolution of the context of the topic. For example, it is still unknown how many relevant topics were mentioned in the three phases and what the relationships between the different topics and the different phases are. It is also unknown which articles may have a more critical impact during the different phases. To answer these questions and partly visualize the research frontiers of nanogenerator research, phased bibliographic coupling is introduced and used to approach these questions. The tool of bibliographic coupling analysis is enabled in the software, *CiteSpace*. The indicator used to evaluate the clustering is the silhouette coefficient [24], and the centrality indicator for the nodes of the co-citing network is *betweenness centrality* [25,26]. These two indicators are defined in the following Eqs. (1)–(3).

$$S(i) = \begin{cases} 1 - a(i)/b(i), & if \ \ a(i) < b(i) \ , \\ 0, & if \ \ a(i) = b(i) \ , \\ b(i)/a(i) - 1, & if \ \ a(i) > b(i) \end{cases} \tag{1}$$

In Eq. (1), for each datum ***i*** in dataset ***DS***, ***a(i)*** is the average distance of ***i*** from all other data within the same cluster, ***b(i)*** is the lowest average distance of ***i*** from any other cluster of which ***i*** is not a member, and ***s(i)*** is the silhouette coefficient and falls in the range [−1, 1], as shown in Eq. (2).

$$-1 \le s(i) \le 1 \tag{2}$$

A formal calculation method for *betweenness centrality* is shown in Eq. (3).

$$Centrality(node_i) = \sum_{i \ne j \ne k} \frac{\rho_{jk}(i)}{\rho_{jk}} \tag{3}$$

In Eq. (3), ρ_{jk} represents the number of shortest paths between node j and node k, and $\rho_{jk}(i)$ is the number of those paths that pass through node i. Additionally, in the weighting directed graph, Eq. (3) includes several types of transformation. At the document level, the importance of each document in a co-citing network can be partially evaluated by the indicator *betweenness centrality*. Based on Eqs. (1) and (2) and the bibliometric tool, *CiteSpace*, the results of bibliographic coupling analysis are initially summarized in Table 4.

Based on the results shown in Table 4, the outputs of bibliographic coupling of the relevant articles in the different phases are all significant. The means of the silhouette coefficients in the three phases are all greater than 0.95 and very close to the maximum value of 1. The proportions of the coverage articles in the clustering outputs all exceed 98% in the three phases. At the same time, there are some differences between the three phases. For example, although the number of articles in the third phase is the largest and is in fact larger than the total in the prior two phases, the convergence trend in the research topics appears to be significant, based on the largest mean size and mean silhouette in the three phases. To visualize the three phases of the relevant research on nanogenerators in greater detail, the bibliographic coupling analyses of the three phases is elaborated in the following.

The first stage is defined as the period of exploration of the fundamental theory of nanogenerators and in which PENG is introduced. The results of the bibliographic coupling analysis of the relevant literature are shown in Fig. 4 and Table 5.

In the first phase, the introduction of PENG is a profound event in 2006, with more and more research focused on highly relevant issues, such as improving the output voltage of the PENG, enhancing the current density, and finding more suitable materials for the piezoelectric effect. In Fig. 4, the blue nodes dispersed in different clusters represent articles with high centrality, and the top 5 articles ordered by centrality are presented in Table 5.

In reviewing the articles in Table 5, it is evident that most of the top

Table 4
Bibliographic coupling analyses of the literature in three phases[a].

Phase	Articles	Clusters (size > =2)	Coverage articles	Mean size	Mean silhouette	Top 3 clusters (plus ties) ordered by size (labeled by Log-likelihood ration, p-value) / **Size of cluster**
I	205	14	202	14.43	0.951	optical properties (91.53, 1.0E-4); atomic formulation (82.3, 1.0E-4); barium titanate (82.3, 1.0E-4); ZnO nanowire array (166.92, 1.0E-4); cavity top (85.36, 1.0E-4); non-epitaxial si (80.58, 1.0E-4); ZnO tetrapod (138.68, 1.0E-4); transport property (119.31, 1.0E-4); electrical properties (80.81, 1.0E-4); ultrasonic wave-driven nanogenerator (87.54, 1.0E-4); energy generation (82.01, 1.0E-4); piezoelectric thin film (82.01, 1.0E-4);
II	292	17	287	16.88	0.957	vinylidene fluoride-trifluoroethylene (351.61, 1.0E-4); piezoelectric effect (290.25, 1.0E-4) / **26** triboelectric nanogenerator (372.86, 1.0E-4); using copper substrate (306.1, 1.0E-4) / **25** surface effect (752.09, 1.0E-4); zinc oxide (293.55, 1.0E-4) / **21**
III	682	28	679	24.25	0.981	vinylidene fluoride-trifluoroethylene (208.53, 1.0E-4); mechanical behavior (204.85, 1.0E-4); nonwoven fiber fabrics (204.85, 1.0E-4) / **43** ferrohydrodynamic energy harvesting (185.38, 1.0E-4); air droplet movement (185.38, 1.0E-4); arch-shape nanogenerator (180.21, 1.0E-4) /**37** roll-printed wrinkled electrode (199.74, 1.0E-4); contact electrification (188.55, 1.0E-4) /**32** triboelectric nanogenerator (379.16, 1.0E-4); emerging energy source (193.03, 1.0E-4) /**32**

[a] The detailed clustering results for the literature of the three phases are shown in the appendix.

5 articles concern the issue of energy harvesting, which could be one of the critical subtopics or core questions within the macro framework of nanogenerators in the first phase. Another interesting phenomenon is found in the fourth article, which is written by top scientists in material science and published in a leading journal in computer science and information systems. Undoubtedly, the fourth article is a typical example of interdisciplinary research, and the core purpose of this article is to introduce a novel self-powered device based on nanogenerator technology, one that can be facilitated by sensors in the application of pervasive computing and the Internet of Things [27]. On the other hand, the relatively small-sized clusters in Fig. 4 partly reflect the diversification of research themes in the first phase and the relevant issues relating to the harvesting of mechanical energy.

In phase II, two additional types of nanogenerators are introduced in 2012. The relevant articles, published in 2013 (reflecting the time lag of publication in different journals), focus on the new types of

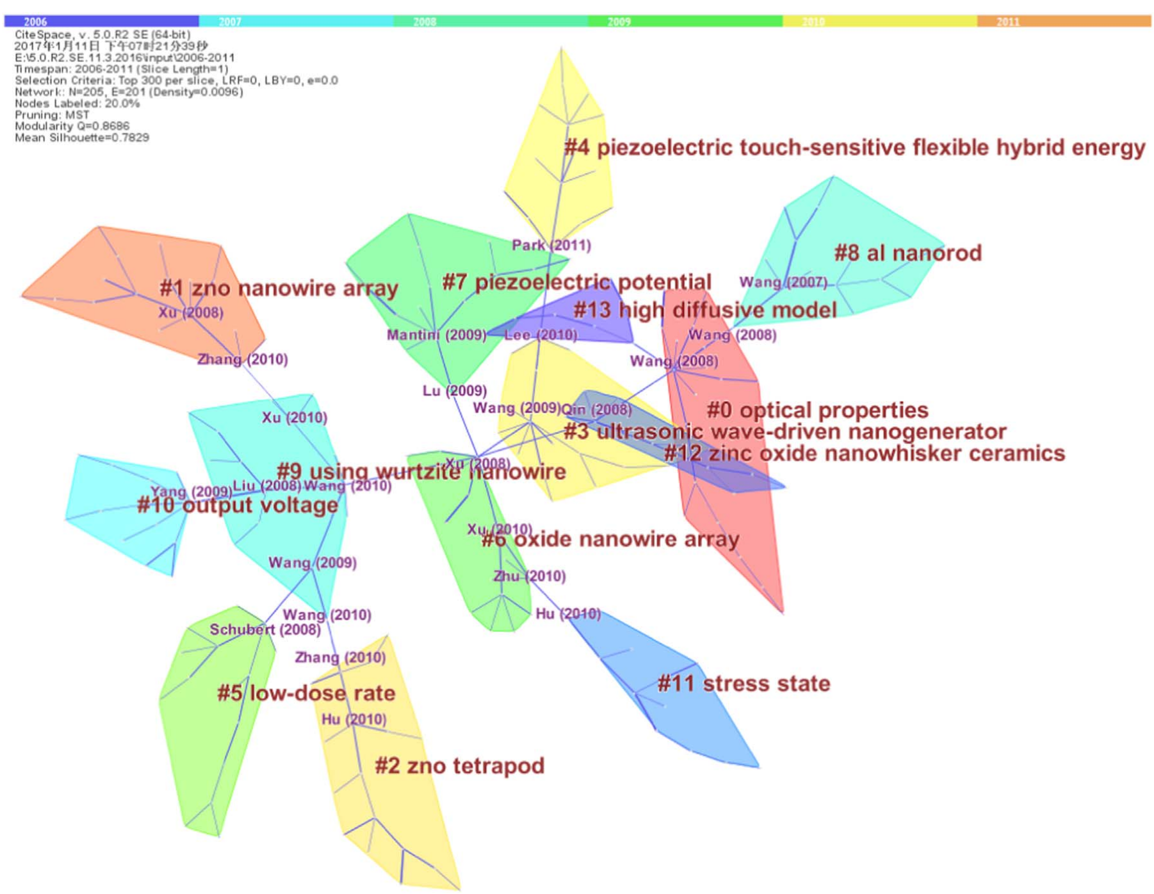

Fig. 4. Bibliographic coupling analysis of the literature of nanogenerator in phase I (2006–2011)**.

Table 5
Top 5 highest centrality articles in Fig. 4.

#	centrality	Article
1	1.45	Xu S., Wei Y., Liu J., Yang R., & Wang ZL. (2008). Integrated multilayer nanogenerator fabricated using paired nanotip-to-nanowire brushes. Nano letters, 8 (11), 4027–4032.
2	1.11	Wang X., Wang ZL. (2010). Mechanical Energy Harvesting Using Wurtzite Nanowires. In Nano-Bio-Electronic, Photonic and MEMS Packaging (pp. 185–216). Springer US.
3	0.77	Qin Y., Wang X., Wang ZL. (2008). Microfibre–nanowire hybrid structure for energy scavenging. Nature, 451(7180), 809–813.
4	0.56	Wang ZL., Wang X., Song J., et al. (2008). Piezoelectric Nanogenerators for Self-Powered Nanodevices. IEEE Pervasive Computing, 7(1), 49–55.
5	0.52	Wang ZL. (2009). Energy Harvesting Using Piezoelectric Nanowires–A Correspondence on "Energy Harvesting Using Nanowires?". Advanced Materials, 21 (13), 1311–1315.

nanogenerators, including theoretical and performance issues. Therefore, the second phase is a time period in which new types of nanogenerators are advanced. The results of BCA are shown in Fig. 5 and Table 6.

In Fig. 5, the clustering result contains 17 clusters and 282 articles, which cover 98.3% of the articles published, and the silhouette among the different clusters is very clear. The top 5 high centrality articles are presented in Table 6.

In the second phase, with the discovery and introduction of new types of nanogenerators (TENG and PRNG) in 2012, many articles concerned with improving the performance and extending the application of nanogenerators were published during these two years. This may be seen as part of the critical frontiers since PENG was introduced in 2006. On the other hand, TENG and PRNG were introduced in 2012 because the effort to enhance the performance of nanogenerators has been an important frontier issue since 2006. In Table 6, the first article proposes a super-flexible nanogenerator that can use a novel active deformation sensor to harvest the energy of gentle wind [28]. The second and fifth articles concern new applications of nanogenerators [29,30]. The third article proposes a novel harvester to improve output voltage through near-field electrospinning [31], and the fourth article introduces a new material, nanowires, that can be utilized by nanogenerators [32]. Overall, in this phase, in addition to the introduction of TENG and PRNG, other relevant research promoting the performance of nanogenerators through new materials, new or more flexible structures, new physical effects, etc., could lead to breakthroughs in the applications of nanogenerators.

With TENG and other more efficient nanogenerators explored and introduced in phase II, the third phase shows a burst in the growth of the relevant literature on nanogenerators. Although the relevant articles published in the third phase exceed the total number of articles published in the prior two phases, the research topics or themes seem more convergent, and the mean size of the clusters is much larger than in the other phases. The results of BCA of the relevant articles in the third phase are shown in Fig. 6 and Table 7.

In Fig. 6, there are 28 clusters whose sizes are larger than 2, covering 679 articles, and the mean silhouette coefficient is larger than 0.98, with a mean size greater than 24; therefore, the research topics of

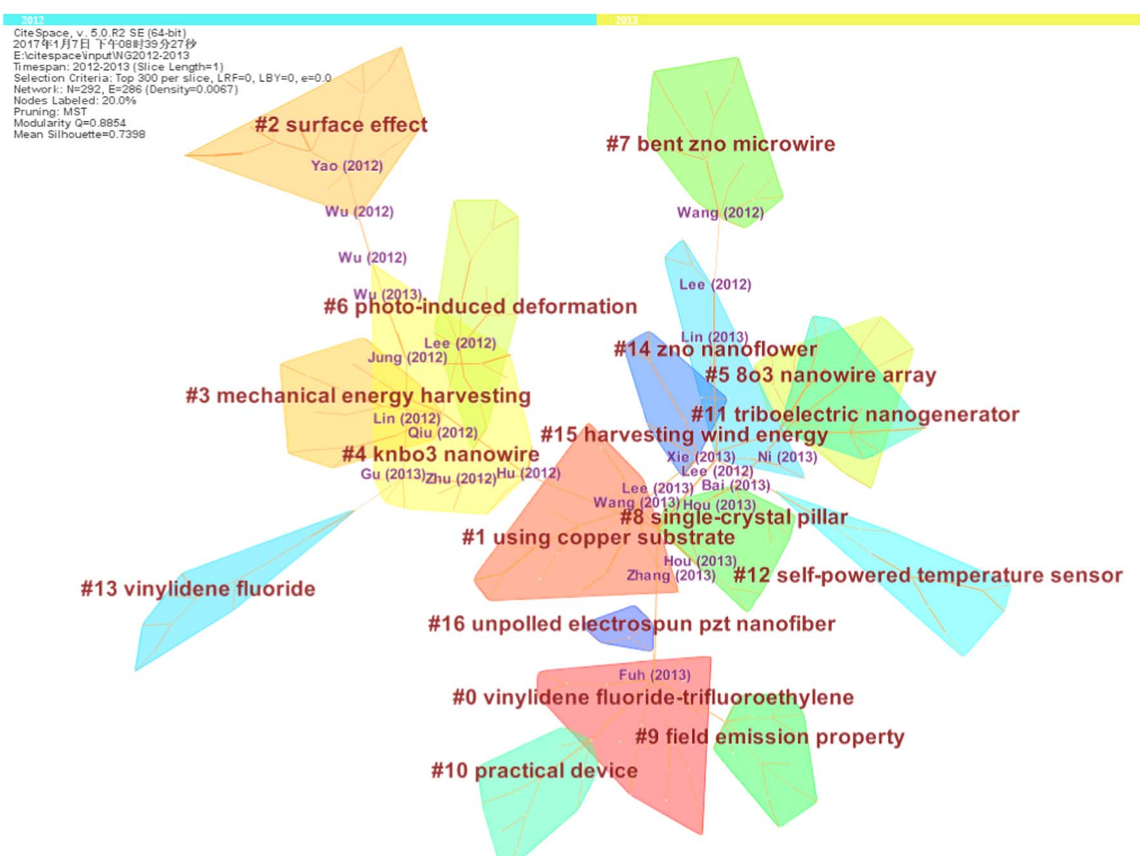

Fig. 5. Bibliographic coupling analysis of the relevant literature in phase II (2012–2013).

Table 6
Top 5 highest centrality articles in Fig. 5.

#	Centrality	Article
1	1.49	Lee S., Bae SH., Lin L., et al. (2013). Super-Flexible Nanogenerator for Energy Harvesting from Gentle Wind and as an Active Deformation Sensor. Advanced Functional Materials, 23(19), 2445–2449.
2	0.95	Hu Y., Lin L., Zhang Y., & Wang ZL. (2012). Replacing a Battery by a Nanogenerator with 20 V Output. Advanced Materials, 24(1), 110–114.
3	0.74	Fuh YK., Chen SY., Ye JC. (2013). Massively parallel aligned microfibers-based harvester deposited via in situ, oriented poled near-field electrospinning. Applied Physics Letters, 103(3), 033114.
4	0.62	Hou TC., Yang Y., Lin ZH., et al. (2013). Nanogenerator based on zinc blende CdTe micro/nanowires. Nano Energy, 2(3), 387–393.
5	0.6	Hou TC., Yang Y., Zhang H., Chen, J., et al. (2013). Triboelectric nanogenerator built inside shoe insole for harvesting walking energy. Nano Energy, 2(5), 856–862.

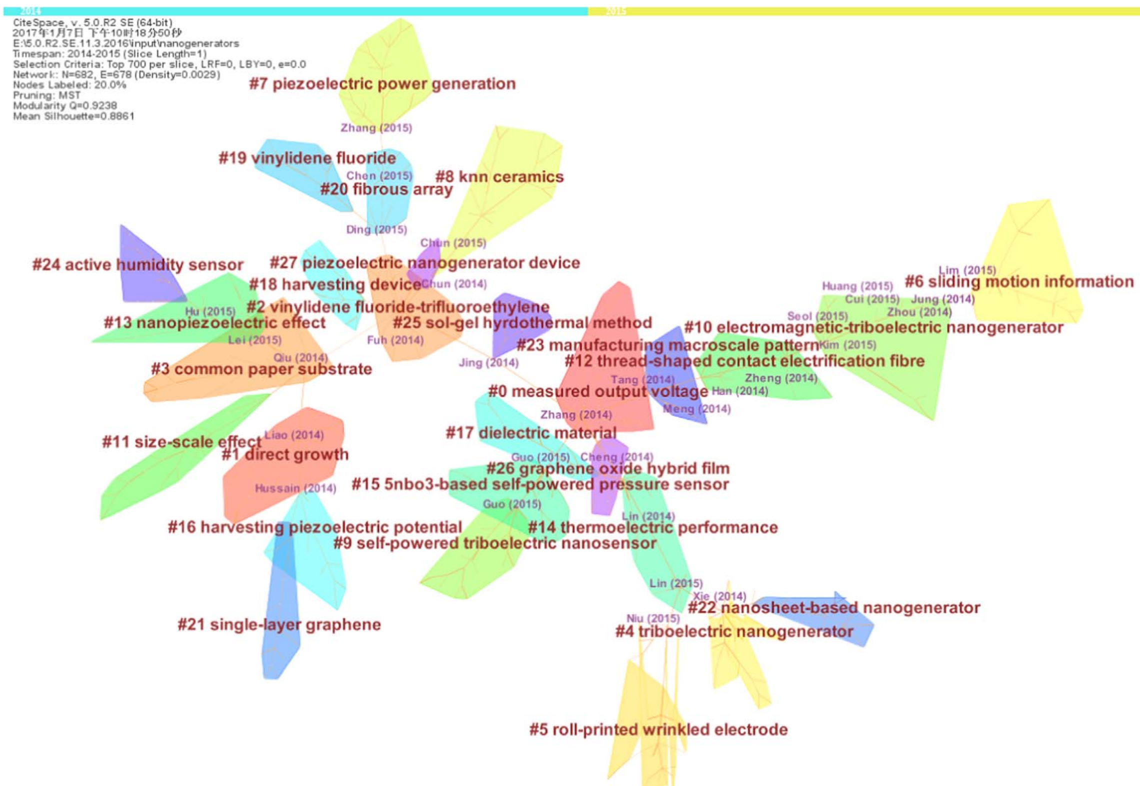

Fig. 6. Bibliographic coupling analysis of the relevant literature in phase III (2014–2015).

Table 7
Top 5 highest centrality articles in the Fig. 4.

#	Centrality	Article
1	1.33	Zhang C., Zhou T., Tang, W., Han C., et al. (2014). Rotating-Disk-Based Direct-Current Triboelectric Nanogenerator. Advanced Energy Materials, 4(9).
2	1.32	Fuh YK., Ye JC., Chen, PC., et al. (2014). A highly flexible and substrate-independent self-powered deformation sensor based on massively aligned piezoelectric nano-/microfibers. Journal of Materials Chemistry A, 2(38), 16101–16106.
3	1.03	Jing Q., Zhu G., Bai P., et al. (2014). Case-encapsulated triboelectric nanogenerator for harvesting energy from reciprocating sliding motion. ACS nano, 8(4), 3836–3842.
4	0.85	Qiu Y., Lei J., Yang D., et al. (2014). Enhanced performance of wearable piezoelectric nanogenerator fabricated by two-step hydrothermal process. Applied Physics Letters, 104(11), 113903.
5	0.62	Cheng G., Lin ZH., Du Z., & Wang ZL. (2014). Increase Output Energy and Operation Frequency of a Triboelectric Nanogenerator by Two Grounded Electrodes Approach. Advanced Functional Materials, 24(19), 2892–2898.

the articles published in phase III present more divergent than those published in the prior two phases, and the mean size of clusters is also much larger, the clustering performance is the best among the three phases, based on the mean silhouette coefficient. Basically, more articles focus on the emerging applications of nanogenerators in areas such as smart wearable devices, wind energy harvesting and solar cell enhancing. In Table 7, the top 5 highest centrality nodes (articles) are presented.

In Table 7, the highest-centrality article proposes a new TENG with output of the direct current based on a specific rotating-disk component and rotating mechanical energy, which could signal a revolutionary improvement and bridge many different research topics related to nanogenerators, including theoretical and application issues [33]. The second article is very close to the first article in terms of centrality;

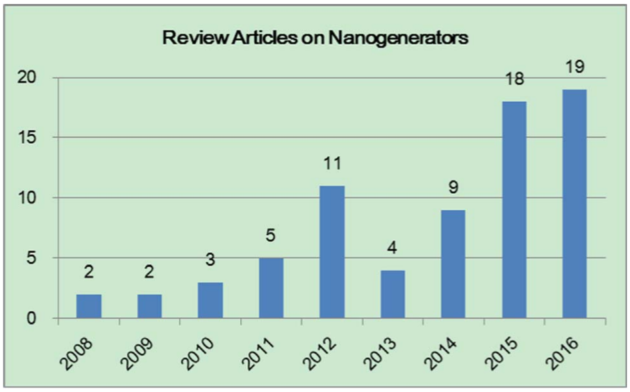

Fig. 7. Relevant review articles on nanogenerators in WOS.

however, the second article concerns PENG, and it proposes a self-powered deformation sensor based on a new structure design of piezoelectric nano/microfibers [34].

The third article proposes a new TENG-cTNEG (case-encapsulated triboelectric nanogenerator), which can not only harvest the energy of reciprocating sliding motion but also that of the energy of vibration [35]. Thus, such a nanogenerator could have promising applications. The fourth article, also related to PENG, proposes a wearable PENG [36]. The fifth article proposes a method of increasing energy output and the operational frequency of a TENG [37]. Based on the analyses of the top 5 high-centrality articles in Table 7, it is partially concluded that many articles have focused on basic issues concerning TENG and PENG, especially the applications of TENG and PENG to wearable devices, self-powered deformation sensors, etc. On the other hand, another new nanogenerator, PRNG, may be limited in its uses. Relevant research articles comparing PRNG with the other two types of nanogenerator remain rare; however, PRNG could be integrated into those emerging applications with PENG and TENG, and then maybe imply a specific facet of the research fronts on nanogenerators in the future [38,39].

5. Review of reviews

By December 2016, some 73 review articles related to nanogenerators could be found in the WOS database. To compare them with the outputs of the prior analyses, these review articles written by domain experts are outlined in Fig. 7.

In 2008, the first review article on nanogenerators was published in the *Journal of Nanoscience and Nanotechnology*, and it reviewed the growth phenomena, unique properties and exciting applications of oxide nanowires and nanobelts [40]. Before 2012, most relevant reviews of nanogenerators focused on the materials of nanogenerators, particularly materials in the wurtzite family, including ZnO, GaN, and InN [41,42]; furthermore, in 2011, sulfide (e.g., ZnS) and nitride (e.g., GaN) were introduced for their potential piezoelectric or optoelectric properties [43,44].

In 2012, 11 review articles on nanogenerators were published, which is almost equal to the total number published between 2008 and 2011. A prominent characteristic of these 11 reviews is that most of them focus on the development of PENGs [45,46] and the emerging applications of PENGs in solar cell and self-powered micro/nanosystems [47].

In 2013, review articles on TENGs began to emerge in different journals about nanotechnology, material science and so forth, and 11 review articles on TENG were published between 2013 and 2016 [48,49]. Meanwhile, 20 review articles related to PENG were published [50,51]. In contrast, only 6 reviews were relevant to PRNG, and five of them were also related to PENG [52]. In addition, seven reviews of graphene-based materials for nanogenerators were published since 2013 [53,54], and there were 14 review articles that explicitly focused on the energy harvesting of nanogenerators, including PENG, TENG and PRNG [55,56].

In the past three years, III-nitride nanomaterials have been widely explored due to their high piezoelectric coefficients and their strong piezogeneration response. The relevant research was then reviewed in 2016 [57]. Similarly, the piezo-phototronic effect was reviewed in 2016 for its promising potential in enhancing the energy harvesting of solar cells [58]. Meanwhile, paper-based electronics [59], flexible and stretchable nanogenerators and their applications in healthcare, self-powered electronics and so forth were re-reviewed to examine the significant progress [60,61]. In addition, another two important review articles focused on TENGs; in particular, one of them introduced and reviewed a new field-tribotronics that couples triboelectricity and semiconductors and could be taken into account in another original and novel field in the development of nanoenergy and nanoelectronics [62].

Compared with the reviews from domain experts, the analyses based on phased bibliographic coupling in this paper could provide a relatively holistic visualization of the evolution of the relevant research on nanogenerators, although the results of the bibliometric analysis could be controversial and somewhat shallow. To some extent, these bibliometric analyses could be more significant for the diffusion of knowledge related to nanogenerators and their relevant topics, particularly for interdisciplinary or new researchers.

6. Conclusions and implications

During the past five years, relevant publications related to nanogenerators in WOS have increased exponentially, especially in the past two years; in contrast, relevant publications on nanotechnology have shown only modest annual growth. To show this phenomenon in light of the differing times of emergence of three typical nanogenerators (PENG, TENG and PRNG), a novel approach, phased biographic coupling, is utilized to explore the evolutionary trend of research related to nanogenerators.

Based on the coupling network and clustering analyses, research on nanogenerators is found to have experienced two critical milestones. One is the invention and publication of PENG in 2006, and the other is the invention and publication of TENG in 2012. With the emergence of TENG and improvements in the output of PENG, the relevant research on nanogenerators appears to have entered into a period of rapid growth; more and more articles introducing the potential application of nanogenerators were published in widely diversified categories of WOS since 2014, e.g. *Biophysics*, *Computer Science Information Systems*, *Computer Science Interdisciplinary Applications*, *Biomedical Engineering*, *Medical Informatics* and *Plant Sciences* so forth. In particular, with the development of pervasive computing technologies, the Internet of Things, wearable electronic devices, renewable energy (wind energy, solar cell, etc.), etc., emerging applications of nanogenerators could play a promising role in the future. In addition to the general trend of nanogenerator research, the highly cited and high-centrality articles in different phases are identified and analyzed to reveal more detailed information about the relevant research.

In the past three years, issues related to nanogenerators have begun to attract more attention from researchers in different fields of science and technology than ever before. Although in the past three years, interdisciplinary research on nanogenerators has emerged in areas such as smart wearable devices, self-powered deformation sensors, and wind and solar cell energy, the most highly cited and high-centrality articles are concentrated in material sciences and nanotechnology. By contrast, in potential interdisciplinary areas, such as computer science, networks and communication, information systems, and renewable energy, relevant articles are still very rare; on the other hand, these interdisciplinary areas could provide space for future developments, leading to more promising applications.

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