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Metamaterials Research: A Scientometric Assessment of Global Publications Output during 2007-16

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ABSTRACT

The paper examines 9858 global publications output on metamaterials research, as covered in Scopus database during 2007-16. The study reveals that metamaterials research registered 15.27% growth and averaged citation impact to 10.08 citations per paper. The global share of top 10 most productive countries in metamaterials research is 84.97 % and their individual global share ranged from 3.30% to 25.57%. China accounted for the largest global share (25.71%), followed by USA (23.96%), U.K. (6.06%), India (5.26%), etc. Five of top 10 countries scored relative citation index above the world average i.e. more than 1: Germany (2.06), USA (1.81), U.K. (1.49), Canada (1.03) and Spain (1.01). The international collaborative publications share of top 10 most productive countries varied from 6.14% to 59.80%. Physics and astronomy, among subjects, contributed the largest publication share (59.36%), followed by engineering (56.71%), materials science (33.30%), computer science (20.32%), mathematics (6.74%) and chemistry (4.46%). The top 20 most productive organisations and authors together contributed 24.69% and 13.17% global publications share respectively and 35.72% and 25.96% global citation share respectively. The top 20 journals accounted for 45.97% share of global output (5743 papers) reported in journals. Of the total global output on metamaterials research, 52 papers were found as highly cited papers averaging 535.64 citations per paper in 10 years. These 52 highly cited papers involved the participation of 310 authors and 142 organisations and were published in 20 journals.

Keywords: Metamaterials; Global publications output; Bibliometrics; Scientometrics

1. INTRODUCTION

Metamaterials are the future materials that can be used to control and manipulate the flow of light, sound, and generate such other exceptional properties, not found in nature or in naturally occurring materials. Metamaterials scientific activity is centred mainly on the electromagnetic properties. Meta-materials gain their exotic and unprecedented electromagnetic properties from their structure rather than from their composition. Metamaterials are not constructed at the chemical level, as is ordinarily done, but by altering and controlling the internal physical structure of macro cellsat sub-wavelength level in a specified way so that such materials exhibit exceptional electromagnetic properties that do not exist in nature. Meta-material-enabled devices have a wide range of applications in the RF, THz, IR, and visible spectrum[1]. Metamaterial-enabled imaging systems can be integrated with computational imaging paradigms[2]. Meta-materials can be used to develop new generation, lightweight, high-gain, rapidly reconfigurable soft-ware defined antennas having potential for applications in wireless communication, battlefield communications, cellular systems and high frequency backhaul, and even enterprise Wi-fi systems communication[3]. Acoustic metamaterials can be used in medical ultrasonography, millimeter-precision gesture readers for human-machine interfaces, and near-range sonars for small aircraft[4]. Other astounding advantages of meta-materials include (but are not limited to) negative index of refraction (where magnetic and electric response are simultaneously negative), and 'Perfect' (sub-wavelength) lensing, and electromagnetic 'invisibility' cloaks. Meta-materials hold a huge potential for developing in the near future three-dimensional optical meta-materials, nonlinear meta-materials and leading research into 'quantum' perspectives of meta-materials[1,4].

Metamaterial research being interdisciplinary in nature, numerous research groups around the world in particular in physics, optics, materials, nano-science, and/or electrical engineering are active in developing new technologies and applications in this new and emerging technological discipline of meta-materials. Given this context, it is desirable that a bibliometric study is undertaken for understanding publications and citations trends in metamaterials research at international level.

1.1 Literature Review

There were very few papers on quantitative analysis of

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metamaterials literature and quite a few on materials research as a whole and on individual materials. Adams and Pendlebury[2] reviewed materials S&T, a core area of research of profound interest in most economies because of its potential contribution to manufacturing processes and innovative products. The authors examined the origin and nature of the field, then reviews its growth globally and identify some key players and finally looks selectively at some of its current diversity in 'hot topics' such as grapheme, metal-organic framework and nano-fibrous scaffolds used in tissue engineering. Kademani[3], *et al.* attempted to highlight quantitatively and qualitatively the growth and development of world literature on materials science in terms of publication output and citations as per Web of Science (2006–2010) database. The parameters studied include growth of publications and citations, continent-wise distribution of publications and citations, country-wise distribution of publications, domain-wise distribution of publications and citations, publication efficiency index, distribution of publications and citations according to number of collaborating countries, variation of mean impact factor in materials science domains, identification of highly cited publications and highly preferred journals, quality of research output and application of Bradford's law. In this Indian context, Kademani[4], *et al.* analysed the materials science literature in India for a period of ten years (1999-2008) and Walke[5], *et al.* and Gupta[6], *et al* reported on the status of materials science research in India during 1993-01, with metrics on its publication size and growth rate, and discussing its media of communication, strength and weakness in the areas of research, quality of research output, nature of collaboration, and institutional productivity

Among metamaterials-based research studies, Jovanovic[7], *et al.* compared the profiles of metamaterials and fullerenes and looked for typical patterns of the trajectories in the publication landscape. Ruihua[8] presented a bibliometric analysis of metamaterial research from 1998 to 2007, using Thomson Data Analyzer (TDA) software and sought to describe distribution of publications output by publication years, countries, subject categories, research institutions, reporting journals, authors and the research subjects. Lheurette[9] presented a brief history of metamaterials research, examined metamaterials global the growth during 2000-2013 and studied distribution of publications across research and application fields. The other studies in materials science are related to graphene[10-11], nanomaterials[12], rare materials[13], etc. reported trends across several different bibliometric indicators.

2. OBJECTIVES

The main objective of this study is to study the performance status of metamaterials research published during 2007-16, based on publication analysis of research output covered in Scopus database. In particular, the study focuses on:

(i) The growth of world research output on metamaterials research, its citation impact and productivity and citation impact of top 10 most productive countries;
(ii) The international collaboration share of top 10 most productive countries;
(iii) The global research output by broad subject areas and the dynamics of its growth and decline;
(iv) To identify significant keywords in metamaterials research;
(v) The publication productivity and citation impact of top 20 most productive organisations and authors;
(vi) The modes of research communication, and
(vii) The characteristics of top 52 highly cited papers**.**

3. METHODOLOGY

The data for scientometric study on metamaterials research was retrieved and downloaded from the Scopus database (http://www.scopus.com) covering the 10 years period 2007-16. A search string was formulated by tagging 'keyword tag' and 'Source Title tag' to the search term 'metamaterial'. In addition the search string was refined by tagging 'date range tag' to search period '2007-16'. For the next round of data searching, the said search string was further refined using analytical commands available in Scopus database, by 'subject area tag', 'country tag', 'source title tag', 'journal title name' and 'affiliation tag' respectively to collect data on publications output by subject, collaborating countries, author-wise, organisation-wise and journal-wise. The raw publications data was analysed across a series of raw and relative bibliometric indicators with a view to understand the dynamics of global research in metamaterials. In conducting data analysis, we used complete counting method wherein every contributing author or organisation covered in multiple authorship papers was fully counted. All authors or organisations to multi-authored papers have received equal credit in data counting and analysis. For impact factor, we used 2015 data. Citations to sourced publications were collected from date of publication till 17 January 2017.

(KEY (metamaterial) OR TITLE (metamaterial)) AND PUBYEAR > 2006 AND PUBYEAR < 2017

4. ANALYSIS

4.1 Publications Analysis

The global research output on metamaterials cumulated to a total of 9858 publications in 10 years during 2007-16, growing at 15.27 % from 423 in 2007 to 1480 publications in 2016. The metamaterials research registered 98.09 % quinquennial growth from 3307 to 6551 publications during the period 2007-11 to 2012-16. The citation impact of global publications on metamaterials averaged to 10.08 citations per publication (CPP) during 2007-16, but their five-yearly impact declined from 20.09 CPP to 5.03 CPP during 2007-11 to 2012-16 as shown in Table 1 and Fig. 1.

Of the total global publications in metamaterials research distributed by document type, 54.75 % (5397) was published as articles, 42.39 % (4179) as conference papers, 0.93 % (92) as reviews, 0.90 % (89) as articles in press, and the rest as book chapters (26), erratum's (24), notes (19), short surveys (17), letters (7), editorials (5), conference reviews (2) and book (1). The articles, conference papers and reviews together constitute 98.07 % of the global output on metamaterials.

Table 1. World output in metamaterials research, 2007-16

Publication Period	World		
	TP	TC	CPP
2007	423	7006	16.56
2008	542	13840	25.54
2009	663	13106	19.77
2010	742	13663	18.41
2011	937	18818	20.08
2012	1094	12548	11.47
2013	1170	9176	7.84
2014	1379	6943	5.03
2015	1428	3583	2.51
2016	1480	722	0.49
2007-11	3307	66433	20.09
2012-16	6551	32972	5.03
2007-16	9858	99405	10.08

TP = Total papers; TC = Total citations; CPP = Citations per paper

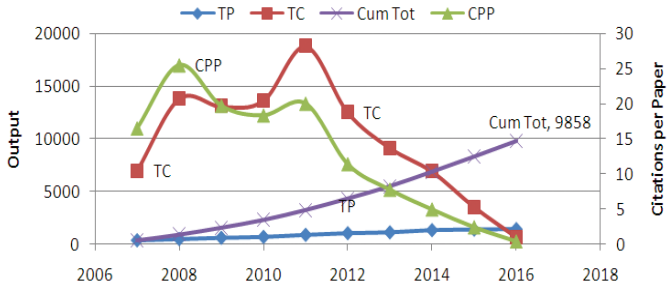

Figure 1. Publications and citations growth in metamaterials: 2007-16.

4.2 Top 10 Most Productive Countries in Metamaterials

The global research output on metamaterials originated from as many as 88 countries during 2007-16. The distribution of research output by country of publication is highly skewed. The top 10 most productive countries in metamaterials research accounted for 84.97 % global shared uring 2007-16 as shown in Table 2. Their five-yearly global publication share dropped from 85.09 % to 84.90 % during 2007-11 to 2012-16. Of the 88 countries, 34 contributed 1-10 papers each, 20 countries 11-50 papers each, 13 countries 51-100 papers each and 17 countries 101-500 papers each, 2 countries each 501-1000 and 2001-3000 papers each. Their global share ranged between 3.30 % and 25.57 % during 2007-16, with China accounting for the highest global share (25.71 %), followed by USA (23.96 %), U.K. (6.06 %), India (5.62 %), South Korea (4.95 %), Germany (4.37 %), France (4.0 %), Japan (3.72 %), Spain (3.42 %) and Canada (3.30 %) during 2006-17. The five-yearly cumulative output of China increased by 7.27 %, followed by 5.86% in India, 1.14 % in Japan and 0.28% in France, whereas it decreased by 6.63 % in USA, 3.32% in Spain, 3.07 % in Germany, 0.86 % in Canada, 0.53% in U.K. and 0.33 % in South Korea during 2007-11 to 2012-16. Five of top 10 countries scored relative citation index above the world average *i.e.* more than 1: Germany (2.06), USA (1.81), U.K. (1.49), Canada (1.03) and Spain (1.01) during 2007-16.

4.3 International Collaboration

The national share of international collaborative papers across top 10 countries in metamaterials research varied from 6.14 % to 59.80 %, with U.K. (59.80 %) accounting for the highest national share, followed by Germany (52.90%), Spain (51.34 %), France (47.97%), Canada (40.0 %), USA (33.19 %), Japan (29.16 %), China (22.49 %), South Korea (20.70 %) and India (6.14 %) during 2007-16 as shown in Table 2.

4.4 Subject-Wise Distribution of Research Output

The global research output on metamaterials reported during 2007-16 spreads across six sub-fields (as identified in Scopus database classification), with physics and astronomy accounting for the highest publications share (59.36 %),

Table 2. Global publication share of top 10 most productive countries in metamaterials during 2007-16

Name of the Country	Number of Papers			Share of Papers			TC	CPP	ICP	% ICP	RCI
	2007-11	2012-16	2007-16	2007-11	2012-16	2007-16					
China	686	1835	2521	20.74	28.01	25.57	22938	9.10	567	22.49	0.90
USA	938	1424	2362	28.36	21.74	23.96	43133	18.26	784	33.19	1.81
U.K.	212	385	597	6.41	5.88	6.06	8960	15.01	357	59.80	1.49
India	57	497	554	1.72	7.59	5.62	1203	2.17	34	6.14	0.22
South Korea	171	317	488	5.17	4.84	4.95	2906	5.95	101	20.70	0.59
Germany	212	219	431	6.41	3.34	4.37	8934	20.73	228	52.90	2.06
France	126	268	394	3.81	4.09	4.00	2732	6.93	189	47.97	0.69
Japan	98	269	367	2.96	4.11	3.72	2000	5.45	107	29.16	0.54
Spain	186	151	337	5.62	2.30	3.42	3430	10.18	173	51.34	1.01
Canada	128	197	325	3.87	3.01	3.30	3390	10.43	130	40.00	1.03
Total	2814	5562	8376	85.09	84.90	84.97	99626	11.89	2540	30.32	1.18
World	3307	6551	9858	100.00	100.00	100.00		10.08			
Share of 10 countries in world Total	85.09	84.90	84.97	20.74	28.01	25.57	22938	9.10	567	22.49	0.90

TP = Total papers; TC = Total citations; CPP = Citations per paper; ICP = International collaborative papers; RCI = Relative citation index

followed closely by engineering (56.71 %), materials science (33.30 %), computer science (20.32 %), mathematics (6.74 %) and chemistry (4.46 %) during 2007-16. The activity index, which computes changes in research activity in the sub-fields over time 2007-11 to 2012-16 (world average activity index of a given subject being taken as 100), witnessed increase in physics and astronomy (from 99.43 to 100.29), materials science (from 77.09 to 111.57), computer science (from 90.34 to 104.88) and chemistry (from 62.33 to 119.02), as against decline of research activity in engineering (from 104.31 to 97.83) and mathematics (from 101.46 to 99.26) from 2007-11 to 2012-16. Among 6 subjects, chemistry scored the highest citation impact of 18.77 citations per paper, followed by physics and astronomy (13.40), materials science (8.39), engineering (5.88), mathematics (3.04) and computer science (1.65) during 2007-16 as shown in Table 3.

4.5 Top 20 Most Productive Global Organisations

The productivity of top 20 most productive global organisations pursuing metamaterials research varied from 83 to 187 publications in 10 years and together they account for 24.69 % (2434) publication share and 35.72 % (35510) citation share during the period 2007-16. The scientometric profile of these 20 organisations is presented in Table 4. Twelve organisations registered publications output above the group average of 121.7: University of Electronics Science & Technology of China (187 papers), Southeast University, China (169 papers), Air Force Engineering University, China (158 papers),

Table 3. Subject-wise breakup of global publications in metamaterials research during 2007-16

Subject*	Number of papers (TP)			Activity Index		TC	CPP	%TP
	2007-11	2012-16	2007-16	2007-11	2012-16	2007-16	2007-16	2007-16
Physics & Astronomy	1952	3900	5852	99.43	100.29	78426	13.40	59.36
Engineering	1956	3634	5590	104.31	97.83	32895	5.88	56.71
Materials Science	849	2434	3283	77.09	111.57	27549	8.39	33.30
Computer Science	607	1396	2003	90.34	104.88	3310	1.65	20.32
Mathematics	226	438	664	101.46	99.26	2016	3.04	6.74
Chemistry	92	348	440	62.33	119.02	8257	18.77	4.46
World Output	3307	6551	9858	100.00	100.00			

*There is overlapping of literature covered under various subjects; TP = Total papers; TC=Total citations; CPP=Citations per paper

Table 4. Scientometric profile of top 20 most productive global organisations in metamaterials research during 2007-16

Name of the organisation	TP	TC	CPP	HI	ICP	% ICP	RCI
University of Electronics Science & Technology of China	187	1450	7.75	18	39	20.86	0.77
Southeast University, China	169	2872	16.99	28	35	20.71	1.69
Air Force Engineering University, China	158	938	5.94	18	0	0.00	0.59
National University of Singapore	154	1280	8.31	19	93	60.39	0.82
Nanyang Technological University, Singapore	138	1264	9.16	21	100	72.46	0.91
University of Southampton, U.K.	137	3805	27.77	30	90	65.69	2.76
Nanjing University, China	135	2241	16.60	26	27	20.00	1.65
Duke University, USA	124	4615	37.22	30	27	21.77	3.69
Harbins Institute of Technology, China	124	834	6.73	12	46	37.10	0.67
Pennsylvania State University, USA	123	1039	8.45	19	37	30.08	0.84
Zhejiang University, China	123	2833	23.03	25	78	63.41	2.28
Purdue University, USA	123	3416	27.77	25	43	34.96	2.76
Xian Jiaotong University, China	106	591	5.58	14	6	5.66	0.55
University of Arizona, USA	103	1306	12.68	21	33	32.04	1.26
Huazhong University of Science & Technology, China	97	745	7.68	12	6	6.19	0.76
Northwestern Polytechnic University, China	95	992	10.44	19	15	15.79	1.04
Indian Institute of Technology, Kanpur, India	86	459	5.34	12	5	5.81	0.53
Xidian University, China	85	550	6.47	12	0	0.00	0.64
Los Alamos National Laboratory, USA	84	3763	44.80	27	28	33.33	4.44
Orta Dogu Teknik Universitesi (Middle East Technical University), Turkey	83	517	6.23	13	15	18.07	0.62
Total of 20 organisations	2434	35510	14.59	20.05	723	29.70	1.45
Total of World	9858	99405	10.08				
Share of top 20 organisations in world total output	24.69	35.72					

National University of Singapore (154 papers), Nanyang Technological University, Singapore (138 papers), University of Southampton, U.K. (137 papers), Nanjing University, China (135 papers), Duke University, USA (124 papers) and Harbins Institute of Technology, China (124 papers each), Pennsylvania State University, USA and Zhejiang University, China and Purdue University, USA (123 papers each) during 2007-16. Seven organisation registered impact above the group average of 14.59 citations per publication during 2007-16: Los Alamos National Laboratory, USA (44.80), Duke University, USA (37.22), University of Southampton, U.K. and Purdue University, USA (27.77 each), Zhejiang University, China), Southeast University, China (16.99) and Nanjing University, China (16.60) during 2007-16. Nine organisation registered h-index above the group average of 20.05: Duke University, USA and University of Southampton, U.K. (30 each), Southeast University, China, (28), Los Alamos National Laboratory, USA (27), Nanjing University, China (26), Purdue University, USA and Zhejiang University, China (25 each), University of Arizona, USA and Nanyang Technological University, Singapore (21 each) during 2007-16. Nine organisations contributed international collaborative publications share above the group average of 29.70 %: Nanyang Technological University, Singapore (72.46%), University of Southampton, U.K. (65.69 %), Zhejiang University, China (63.41 %), National University of Singapore (60.39 %), Harbins Institute of Technology, China (37.10 %), Purdue University, USA (34.96%), Los Alamos National Laboratory, USA (33.33%), University of Arizona, USA (32.04 %) and Pennsylvania State University, USA (30.08%) during 2007-16. Seven organisation registered the relative citation index above the group average (1.45) of all organisations: Los Alamos National Laboratory, USA (4.44), Duke University, USA (3.69), University of Southampton, U.K. and Purdue University, USA (2.76 each), Zhejiang University, China (2.28), Southeast University, China (1.69) and Nanjing University, China (1.65) during 2007-16.

4.6 Top 20 Most Productive Authors

The research productivity of top 20 most productive authors pursuing in metamaterials research varied from 50 to 116 publication in 10 years. Together they account for 13.17 % (1298) global share and 25.96 % (25803) citation share during 2007-16. The scientometric profile of these 20 authors is presented in Table 5. Eight authors registered publications output above the group average of 64.9: N.I. Zhelude (116 papers), D.H. Werner (84 papers), C. Sabah (83 papers), R.W. Ziolkowski (80 papers), Q. Wu (78 papers), D.R. Smith (73 papers), J. Cui (67 papers) and T. Itoh (65 papers) during 2007-16. Seven authors registered impact above the group average of 19.88 citations per publication: D.R. Smith (54.90), R.D.

Table 5. Scientometric profile of top 20 most productive authors in metamaterials research during 2007-16

Name of the author	Affiliation of the author	TP	TC	CPP	HI	ICP	% ICP	RCI
N.I. Zhelude	University of Southampton, U.K.	116	3751	32.34	30	83	71.55	3.21
D.H. Werner	Pennsylvania State University, USA	84	754	8.98	16	8	9.52	0.89
C. Sabah	Johann Wolfgang Goethe-Universitat Physikalischer Institute, Germany	83	517	6.23	15	82	98.80	0.62
R.W. Ziolkowski	University of Arizona, USA	80	1097	13.71	18	22	27.50	1.36
Q. Wu	Harbins Institute of Technology, China	78	423	5.42	10	32	41.03	0.54
D.R. Smith	Duke University, USA	73	4008	54.90	25	15	20.55	5.45
T.J. Cui	Southeast University, China	67	1697	25.33	21	14	20.90	2.51
T. Itoh	University of California, Los Angles, USA	65	763	11.74	12	32	49.23	1.16
G.V. Eleftheriades	University of Toronto, Canada	62	932	15.03	16	4	6.45	1.49
F.V. Meng	Harbins Institute of Technology, China	58	314	5.41	10	28	48.28	0.54
C. Rockstuhl	Friedrich-Schilles University of Jena, Germany	56	1527	27.27	20	30	53.57	2.71
R.D. Averitt	Boston University, USA	55	2857	51.95	15	10	18.18	5.15
R. Singh	Los Alamos National Laboratory, USA	55	1708	31.05	19	47	85.45	3.08
M. Beruete	University Publica de Navarra, Spain	54	391	7.24	12	35	64.81	0.72
V.A. Fedotov	University of Southampton, U.K	54	2034	37.67	16	36	66.67	3.74
M.T. Islam	Univkabangssan Malaysia	53	342	6.45	10	5	9.43	0.64
T. Martin	Univ Autonoma de Barcelona, Spain	53	696	13.13	13	8	15.09	1.30
E. Ozbay	Bikent University, Turkey	52	939	18.06	15	23	44.23	1.79
W.J. Padilla	Boston College, USA	50	568	11.36	20	5	10.00	1.13
Z. Xu	Xian Jiaotong University, China	50	485	9.70	12	2	4.00	0.96
	Total of 20 authors	1298	25803	19.88	16.25	521	40.14	1.97
	Total of World	9858	99405	10.08				
	Share of top 20 authors in world total output	13.17	25.96					

TP = Total papers; TC= Total citations; CPP = Citations per paper; HI = h-index; ICP = International collaborative papers; RCI = Relative citation index

Averitt (51.95), V.A. Fedotov (37.67), N.I. Zhelude (32.34), R. Singh (31.05), C. Rockstuhl (27.27) and T.J. Cui (25.33) during 2007-16. Seven authors registered h-index above the group average of 16.25 of all authors: N.I. Zhelude (30), D.R. Smith (25), T.J. Cui (21), C. Rockstuhl and W.J. Padilla (20 each), R. Singh (19) and R.W. Ziolkowski (18) during 2007-16. Ten authors contributed international collaborative publications share above the group average of 40.14 % of all authors: C. Sabah (98.80 %), R. Singh (85.45 %), N.I. Zhelude (71.55 %), V.A. Fedotov (66.67 %), M. Beruete (64.81%), C. Rockstuhl (53.57 %), T. Itoh (49.23 %), F.V. Meng (48.28%), E. Ozbay (44.23 %) and Q. Wu (41.03 %) during 2007-16. Seven authors registered the relative citation index above the group average (1.97) of all authors:.R.Smith (5.45), R.D. Averitt (5.15), V.A. Fedotov (3.74), N.I. Zhelude (3.21), R. Singh(3.08), C. Rockstuhl (2.71) and, T.J. Cui (2.51) during 2007-16.

4.7 Medium of Research Communication

Of the total global output on metamaterials research distributed by source type, 58.26 % (5743) appeared in journals, 40.34 % (3977) in conference proceedings, 0.84 % (83) in book series, 0.29 % (29) in books and 0.26 % (26) in trade publications. The top 20 most productive journals each reported 62 to 334 papers, together these 10 journals accounted for 45.97 % share (2640 papers) of total journal papers during 2007-16. The publication share of top 20 most productive journals dropped from 49.97 % to 44.12 % between 2007-11 and 2012-16. *Applied Physics Letters* emerged as the top most productive journal in meta-materials (with 334 papers), followed by *Optical Express* (300 papers), *Microwave & Optical Technology Letters* (264 papers), *IEEE Transactions on Antennas & Propagation* (190 papers), etc. during 2007-16 as shown in Table 6.

4.8 Significant Keywords

Top significant keywords have been identified from the literature, which point towards possible directions of research trends in meta-materials. These keywords are listed in Table 7 in the decreasing order of the frequency of occurrence during 2007-16.

4.9 Highly Cited Papers

Of the total global output of 9858 papers on meta-materials, 52 were identified as highly cited papers, each with high-end citations ranging from 201 to 7030 citations per paper during 2007-16. These 52 highly cited papers together cumulated 27852 citations in 10 years, and averaged 535.64 citations per paper. Of the 52 highly cited papers, 13resulted from single stand-alone organisations (as non-collaborative papers) and 39 from collaborative participation across two or more organisations (as collaborative papers, 21 from across national collaboration and 18l from across international collaboration). Among international collaborative papers, the country participation was the largest from USA (38 papers), followed by China (12 papers), U.K. (6 papers), Germany (5 papers), Greece and Denmark (2 papers each), Russia Federation, Sweden, Ukraine, Belgium, Portugal, Brazil, Spain, Canada, Japan, France, South Korea, Hong Kong and Italy (1 paper each). These 52 highly cited papers resulted from research pursuits by a total of 310 authors and 142 organisations. The significant authors contributing to high cited papers include N.I. Zhelude (16 papers), Z. Xu (10 papers), V.A. Fedotov, D.R. Smith and C.M. Soukoulis (9 papers each), A. Taylor, H. Chen and W. Zhang (7 papers), C. Rockstuhl, R.D. Averitt, R. Singh, A. Alu, X. Zhang, E. and N. Engheta (6 papers each), F.K. Lederer and A.V. Kildishev (5 papers each), V.M. Shalaev, T. Cui and X. Zhang (4 papers each), K. Fan, T. Itoh and E. Ozbay (3 papers each), etc. The significant organisations contributing to high cited papers include University of Southampton, U.K. (16 papers), Los Alamos National Laboratories, USA (14 papers), Purdue University, USA (12 papers), Boston College, USA (11 papers), Zhejiang University, China, Iowa State University, USA and Duke University, USA (9 papers each), Southeast University, China (8 papers), Boston University, USA (7 papers), Nanjing University, China, university of Texas at Austin, USA, Massachusetts Institute of Technology, USA, Friedrich Schiller Universidad, Jena, Germany and The Royal Institute

Table 6. Top 20 most productive journals in metamaterials research during 2007-16

Name of the Journal	Number of Papers		
	2007-11	2012-16	2007-16
Applied Physics Letters	123	211	334
Optical Express	132	168	300
Microwave & Optical Technology Letters	98	166	264
IEEE Transactions on Antennas & Propagation	64	126	190
Journal of Applied Physics	51	121	172
IEEE Antennas & Wireless Propagation Letters	65	101	166
Applied Physics A	30	95	125
Physical Review B	66	58	124
Wuli Xuebao Acta Physica Sinica	43	74	117
Optical Letters	47	59	106
Optics Communication	27	68	95
Journal of Electromagnetic Waves & Applied	24	67	91
Scientific Reports	0	75	75
Progress in Electromagnetic Research	15	58	73
Optik	4	68	72
IEEE Transactions on Microwave Theory & Techniques	35	34	69
Journal of Physics D	14	55	69
Nano Letters	17	52	69
Physical Review Letters	40	27	67
Chinese Physics B	11	51	62
Total of 20 journals	906	1734	2640
Total global journal output	1813	3930	5743
Share of top 20 journals in global journal output	49.97	44.12	45.97

Table 7. Significant keywords in literature on metamaterials research during 2007-16

Keyword	Frequency
Metamaterials	7862
Metamaterials Antennas	1293
Antennas	973
Resonators	783
Metamaterial Structures	759
Polarisation	679
Plasmons	620
Metamaterial Absorbers	583
Ring Gages	548
Microstrip Antennas	545
Electromagnetic Waves	519
Optical Resonators	515

of Technology, Denmark (5 papers each), Technical University of Denmark and University of California, San Diego, USA (4 papers each), Bilkent University, Turkey, University of California, Los Angles, USA, Tiajin University, China and National Taiwan University (3 papers each), etc.

Of the 52 highly cited papers, 49 were published as articles, 1 each as a review paper, conference paper and short survey. These 52 highly cited papers appeared in 20 journals; *Physical Review Letters* (IF=5.93) published 9 papers, 7 papers were published in *Science* (IF=14.23), 6 papers in *Nature* (IF=38.138), 3 papers each in *Optics Express* (IF=3.148), *Applied Physics Letters* (IF=2.99), *Nature Photonics* (IF=31.167) and *Physical Review B* (IF=3.718), 2 papers each in *Nature Nanotechnology* (IF=35.267), *Nano Letters* (IF=14.74), *Nature Materials* (IF=38.89), *Nature Communications (IF=11.05)* and *IEEE Transactions on Antennas & Propagation* (IF=2.053), and 1 paper each in *Nature Biotechnology* (IF=13.45), *Journal of Physics D* (IF=2.772), *Physics-Uppekhi* (IF=2.126), *Advanced Materials Research* (IF=0.23), *IEEE Antennas & Propagation Magazine* (IF=0.896), *Journal of Magnetism & Magnetic Materials* (IF=2.357) and *Optical Material Express* (IF=2.657).

5. SUMMARY AND CONCLUSIONS

Metamaterials are artificial composite material with exotic material properties, unprecedented electromagnetic properties not available from natural materials, and intriguing phenomena and applications. Meta-materials hold a huge potential for developing in the near future three-dimensional optical meta-materials, nonlinear meta-materials and leading research into 'quantum' perspectives of meta-materials.

This paper provides a quantitative and qualitative description of metamaterials research by analyzing global publications data on the subject sourced from Scopus database covering 10 years period during 2007-16. This study finds that metamaterials is still a young and growing research field, multi-disciplinary in nature, involving disciplines such as physics (59.36%), engineering (56.71%), materials science (33.30%), computer science (20.32%), mathematics (6.74%) and chemistry (4.46%). Its global literature in 10 years did not grow as high as expected but it could cumulate its global output to 9858 publications only with 15.27% growth during 2007-16.

Currently, the distribution of metamaterials research output is highly skewed. The top 10 countries in the world account for the largest 85% global share in metamaterials. China and the USA are seen the world leaders in metamaterials accounting for nearly 50% global share whereas other contributing countries like the UK, India, South Korea, Germany, France, and Japan are distant cousins, accounting for a small, 3.72% to 6.0% of the world global share. Of the top 20 most productive global organisations, which account for nearly 25.0% global share, 15 are from either China or the USA. Metamaterials research has been found to be a highly collaborative research activity across top 10 most productive world countries. However, the UK accounts for the highest national share in terms of international collaborative papers (59.80%), followed by Germany (52.90%), Spain (51.34%), France (47.97%), Canada (40.0%), USA (33.19%), Japan (29.16%), China (22.49%), South Korea (20.70%) and India (6.14%) during 2007-16. This data demonstrates that research collaboration at national and international level did play a big role in making breakthroughs in metamaterials research, technology, and applications.

Both USA and China have emerged as world leaders in quality of research in metamaterials accounting for 50 of the top 52 highly cited papers in the field. These 52 highly cited papers together cumulated 27852 citations in 10 years, and averaged 535.64 citations per paper. These 52 highly cited papers appeared in high-impact journals like *Physical Review Letters, Science*, *Nature*, *Applied Physics Letters, Nature Photonics* and *Physical Review B*, *Nature Nanotechnology, Nano Letters, Nature Materials, Nature Communications, IEEE Transactions on Antennas & Propagation*, *Nature Biotechnology, Journal of Physics D, Physics-Uppekhi, Advanced Materials Research, IEEE Antennas & Propagation Magazine, Journal of Magnetism & Magnetic Materials* and *Optical Material Express*. Five of the top 10 countries scored relative citation index above the world average i.e. more than 1: Germany (2.06), USA (1.81), U.K. (1.49), Canada (1.03) and Spain (1.01) during 2007-16.

In order to further stimulate research and development in metamaterials for societal and technological applications, research collaboration in this field at national and international level is essential. Besides, such a collaborative approach to metamaterials research will help facilitate an effective use of existing human/equipment resources, and in addition provide a forum for coordinated research planning, sharing of research facilities and planning joint project supervision.

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