

# Method for collecting and processing keywords

## Analysis of the paper search results from Institute of Electrical and Electronics Engineers (IEEE) and Optica

To find the trends in research related to phase change materials (PCMs), a keyword search for the academic peer-reviewed papers is conducted. As an initial step, the paper search services of Institute of Electrical and Electronics Engineers (IEEE) and Optica (formerly known as The Optical Society, OSA) were selected to collect papers related to PCMs.

One notable search feature of the IEEE and OSA paper search services is that the citation information includes the keywords selected by the authors. For example, suppose paper A has been retrieved by searching with the search word “phase change material”. The citation data bundled with the paper search result contain author-selected keywords such as germanium compounds, thermal conductivity, random-access storage, etc.

The idea of estimating research trends is that these keywords are closely related to the search word “phase change material.” If the keywords are repeatedly seen in other searched papers as well, it can be regarded that those keywords are more popular among researchers and there might be a strong research trend represented by the keywords.

Selection of IEEE and Optica paper archives was determined in terms of the application area. While IEEE papers focus more on electronics-related research issues, Optica focuses on optics. Thus, the keyword searches with “phase change material” for both paper archives are expected to provide PCM research trends in (i) electronics in general and in (ii) optics.

Table 1 shows the top 30 keywords appeared in the search result (with “phase change material”) sorted by the appearing frequency. In order to put a bound in the research trend period, the search is filtered from the year 2004 to 2022. “Phase change material” is provided as the search word. IEEE search services (<https://ieeexplore.ieee.org/search/advanced>) generated a total of 5891 results and Optica (<https://www.osapublishing.org/search.cfm>) generated 974 papers, as of December 8, 2019. Since manually retrieving all the search results from the web pages takes excessive time and effort, the first 1000 search results from IEEE and 500 searches from OSA results are selected to further analyze the keywords listed in the papers.

The keyword information can be extracted from the citation data (RIS format in particular) provided by the search services and a simple Python script was written to extract the keywords. Once the keywords are retrieved, its frequencies are counted and sorted in a descending order. From Figure 1, the keywords chosen by the authors show different trends depending on the search results being from IEEE or OSA archive.

Keyword (IEEE)	counts
Phase change materials	795
phase change materials	755
phase change memories	461
Phase change memory	331
Resistance	202
germanium compounds	193
phase change material	191
Crystallization	179
PCM	161
phase change memory	140
thermal conductivity	130
thermal energy storage	130
antimony compounds	127
Heating	124
Nonvolatile memory	120
Temperature measurement	112
Temperature	111
Thermal conductivity	108
random-access storage	104
Amorphous materials	100
Conductivity	98
Programming	93
Ge <sub>2</sub> Sb <sub>2</sub> Te <sub>5</sub>	90
latent heat	87
Switches	84
Phase change random access memory	79
Electrodes	79
chalcogenide glasses	75
crystallisation	69

Keyword (OSA)	counts
Refractive index	159

Phase shift	108
Laser beams	72
Thin films	67
Phase measurement	63
Phase modulation	53
Scanning electron microscopy	47
Metamaterials	43
Electric fields	42
Optical properties	37
Laser materials processing	35
X ray diffraction	35
Effective refractive index	33
Optical materials	32
Laser materials	30
Material properties	29
Surface plasmons	29
Laser irradiation	27
Absorption coefficient	26
Optical components	26
Spatial light modulators	24
Raman spectroscopy	24
Photonic crystals	23
Electron beam lithography	23
Optical constants	22
Optical data storage	21
Interferometry	19
Fused silica	19
Optical devices	19

Table 1. Top frequency keywords appeared in IEEE and OSA paper search results (with the search word of “phase change material”)

### [Analysis of Nature and Science Magazine paper archives](#)

The same keyword search and frequency-listing method above can be repeated for Nature (<https://www.nature.com/srep/>) and Science Magazine paper search services (<https://advances.sciencemag.org/>). The idea of choosing Nature and Science Magazine is that papers accepted by those organizations are more broadly and generally positioned than by IEEE or OSA. Thus, checking the keywords in Nature or Science Magazine might

produce trend estimations beyond the bounds of electronics or optics applications that were checked in the previous section.

One unfortunate problem with the Nature and Science Magazine paper search services is that the search results do not provide the keyword information selected by the authors. As a second-best measure, the paper titles are separated into words instead and their word frequencies are counted to check the trend. For example, a paper with the title “A map for phase-change materials” generates a word list of “A, map, for, phase-change, materials”. Insignificant words such as a, the, for, and so on are taken out later manually. The same title-breaking step is repeated for other searched paper titles and the frequencies of each word are counted.

For Nature paper archive, a total of 370 results are generated with the search word “phase change material.” The publication time period is bounded from 2004 to 2022. Table 2 shows the first 30 words with the frequency counts sorted in a descending order. While the word listing on the left are not specific as was in Figure 1 where the author-selected keywords are counted, it still shows frequently used words from the paper titles.

In contrast with Nature paper archive search, search for Science Magazine paper archives generated only 33 results. Since this number of articles can be placed in the manual analysis, the word counting of the paper titles are omitted for the Science Magazine articles.

Word (Nature)	counts
map	121
phase-change	77
materials	70
projected	70
memory	69
devices	63
designing	53
crystallization	48
universal	42
neuro-inspired	31
computing	26
rewriteable	25
data	23
storage	23
resonant	22
bonding	22

crystalline	22
comparison	21
study	20
mesoporous	15
silica	15
nanoscale	14
microsphere	13
active	12
carbon	12
used	12
matrix	11
shape-stabilized	10
phase	10

Table 2. Top frequency words from the paper titles that appear in Nature paper search results (with the search word of “phase change material”)

[Analysis of American Institute of Aeronautics and Astronautics \(AIAA\) paper archive](#)

Finally, the word counting of the paper titles is repeated for American Institute of Aeronautics and Astronautics (AIAA) paper archive search results. Since AIAA paper search service does not provide the keywords information selected by the authors either, the paper titles are broken down into words and counted individually.

The purpose of analyzing AIAA paper archive is to find the trends of PCM uses or applications in aerospace or aeronautical fields. Since aerospace engineering requires the state-of-the-art applications of materials used in aircrafts or spacecrafts, estimation of the newest trend in PCM use can be an important information that can help direct (or allocate) future research resources optimally.

Table 3 shows the first 30 words with the frequency counts sorted in a descending order from the AIAA paper search results (with the search word of “phase change material”). As was in the previous cases, the paper publication dates are bounded into from 2004 to 2022. The total of 370 search results are obtained.

Word (AIAA)	counts
laminated	130
composite	80
high	78

conductivity	74
phase	60
change	51
material	50
(pcm)	47
drywall	44
system	39
experimental	38
investigation	33
ice	28
heat	25
exchangers	18
encapsulated	18
slurry	17
flow	17
manifold	17
microchannels	16
graphitized	15
carbon	15
foam	15
with	15
thermal	13
energy	13
storage	12
testing	12
failure	12

Table 3. Top frequency words from the paper titles that appear in AIAA paper search results (with the search word of “phase change material”)