PHOTONICS21

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Exploration of photonics markets

Analysis of US Grants for Photonics R&D Funding

Published by:
Photonics21 – European Technology Platform

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Brussels / Düsseldorf / Paris 2024

Photonics21 has received financial support from the European Commission in the scope of the Coordination and Support Actions "Boosting Europe's Sovereignty in Technology by driving Photonics from Research to Market – Photonics21" – Grant Number 101016520 and "Photonics from Research to Market – Empowering Europe's strategic autonomy, supporting the Green Deal and securing resilience" – Grant Number 101134961.

Analysis of US Grants for Photonics R&D Funding

Contents

1. Evolution of R&D expenses – Worldwide

1.1 Worldwide landscape

Between 2000 and 2019, global R&D spending rose from $725 billion to $2.419 trillion (in $ purchasing power parity), representing annual global growth of 6.4%, compared with global GNP growth of 3.5%. The distribution of this spending worldwide has changed radically (see Figure 1). Like Europe, North America (largely dominated by US contribution) saw its market share decline in global competition in the first decade of the 2000–2010 period, falling from 40% of spending in 2000 to 31% in 2010. Over the last ten years, however, without succeeding in regaining any 'market share', both Europe and the US have come close to annual growth in R&D spending. Their contribution to global R&D expenditure remained stable, from 23% to 22% of global spending (Europe) and 31% to 29% (USA + Canada). China's contribution to global research spending has risen over the same period, from $32.9 billion in 2000 (or 4.5% of global R&D spending) to $525.7 billion (or 21.7% of spending in 2019). This represents an increase in R&D spending at the Chinese level of 15.7% annually over the two decades. However, growth is slowing (>20% between 2000 and 2010 and about 10% in the second decade) (see Table 1).[1]

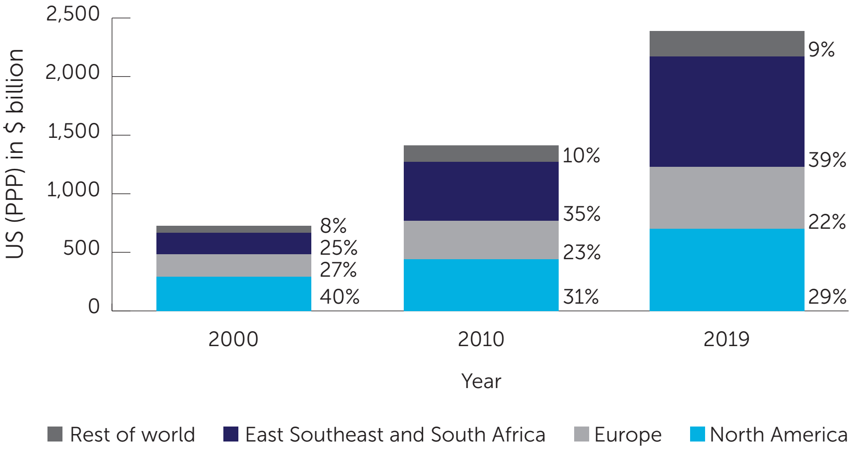


Figure 1: Global R&D expenditures by region: 2000, 2010 and 2019. Source: National Science Board/National Science Foundation. 2022[1], p. 27, based on publicly available data from 2021 from OECD and UNESCO.

[1] National Science Board, National Science Foundation. 2022. Research and Development: U.S. Trends and International Comparisons. Science and Engineering Indicators 2022. NSB-2022-5. Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20225/.

Country	Current measures		Longer-term growth rates				Differential GERD–GDP	
	GERD (ppp US$ billions)	GERD/GDP (%)	GERD		GDP			
			2000–10	2010–19	2000–10	2010–19	2000–10	2010–19
World			**6.6**	**6.3**	**3.5**	**3.4**	**3.1**	**2.9**
United States (2019)[a]	668.4	3.13	4.3	5.6	3.9	4.1	0.4	1.5
China (2019)	525.7	2.23	20.5	10.6	12.9	7.4	7.6	3.2
Japan (2019)	173.3	3.2	3.6	2.4	2.7	2.0	0.9	0.4
Germany (2019)	148.1	3.19	4.9	6.1	3.6	4.3	1.3	1.8
South Korea (2019)	102.5	4.64	10.9	7.8	6.1	3.8	4.8	4.0
France (2019)	73.3	2.2	4.3	4.1	3.9	4.0	0.4	0.1
India (2018)[b]	58.7	0.65	9.4	4.4	9.0	7.0	0.4	-2.6
United Kingdom (2019)	56.9	1.76	4.1	4.7	3.9	3.9	0.2	0.8

Table 1: Comparative growth rates for gross domestic expenditures on R&D and gross domestic product, top R&D performing countries: 2000–10 and 2010–19 (in billions of US PPP dollars and %).[1]
Source: https://ncses.nsf.gov/pubs/nsb20225/cross-national-comparisons-of-r-d-performance

There are wide variations in the allocation of R&D expenditure, depending on the level of maturity of the research carried out (basic, applied, development). While France and the UK invest between 60 and 64% of their expenditure on the most upstream research (basic + applied), China invests 82% on development and the US 64% (see Table 2).

a Data for US GERD differ slightly from the US total R&D. For better consistency with international standards, US GERD includes federal capital funding for federal intramural and nonprofit R&D in addition to what is reported as US total R&D.
b Most recent data for India are 2018. The listed growth rates for India for both GERD and GDP are 2010–18.

Country	Current measures					
	GERD (ppp US$ billions)	GERD/GDP (%)	Basic	Applied	Development	Capex
United States (2019)	668.4	3.13	102.9	132.0	432.0	1.5
China (2019)	525.7	2.23	31.7	59.3	434.7	0.0
Japan (2019)	173.3	3.2	21.7	32.2	112.3	7.1
Germany (2019)	148.1	3.19	N/A	N/A	N/A	N/A
South Korea (2019)	102.5	4.64	15.0	23.1	64.4	0.0
France (2018)	68.6	2.2	15.6	28.3	24.7	0.0
United Kingdom (2018)	54.2	1.76	9.9	22.8	21.5	0.0

Table 2: Gross expenditures on R&D for selected countries, by type of R&D: 2019 or most recent year (in billions of US PPP dollars and %).
Source: https://ncses.nsf.gov/pubs/nsb20225/cross-national-comparisons-of-r-d-performance

1.2 R&D expenditures in the US (post COVID)

On 4 January 2023, the National Center for Science and Engineering Statistics (NCSES), an affiliate of the National Science Foundation (NSF), published its latest figures for US R&D, definitive for 2020 and provisional for 2021.[2]

These figures are obtained from surveys of R&D funders and performers, including both public and private players, which explains the delay in consolidating and publishing the data.

US R&D funding in 2021 is estimated at $789.1 billion, compared with $716.9 billion in 2020, putting it for the second year running at 3.4% of Gross Domestic Product (France's figure is 2.3%; the OECD average is 2.7%). This growth of 10% in value continues into 2022 with a 12% annual growth, leading to US R&D funding about $886 billion in 2022.

In 2021 (the last complete dataset), most of the R&D funding is provided by companies (74.2%), with the federal government contributing 19.2%, corresponding to $148 billion in 2020.

R&D expenditure is mainly carried out by companies (77.2%), universities (10.6%), and federal centres and agencies (8.2%). For 2020, spending can also be broken down into basic research (14.9%), applied research (18.1%) and development (66.9%), compared with the 2019 figures presented above of 15.4% (basic), 19.7% (applied) and 64.6% (development), reflecting an increase in the weight of the R&D activities closest to the market (see Figure 2).

It should be noted that while basic research is still mainly carried out in universities (44.4%), the proportion carried out in companies has risen steadily over the past decade, reaching 34.6% in 2021. Companies also account for 61.1% of applied research spending and 91.3% of development spending. The main driver of R&D funding in the US today is, therefore, primarily business.

[2] The US R&D increased by $51 billion in 2020 to $717 billion; Estimate for 2021 indicates further increase to $792 billion | NSF – National Science Foundation

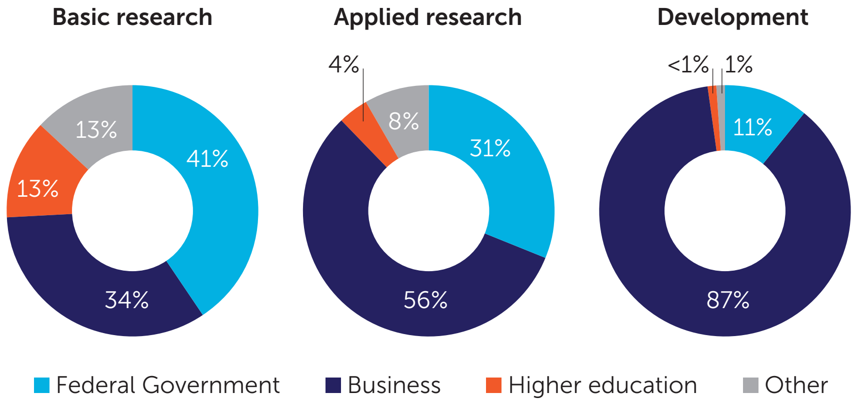


Figure 2: Composition of US basic Research, Applied Research, and Development by Funding sector, 2020, Source: CRS Report US Research and Development Funding and Performance: Fact Sheet Updated 13 September 2022, R44307 (congress.gov).

Source: CRS analysis of National Science Foundation, National Patterns of R&D Resources: 2019–20 Data Update, *NSF 22–320, Tables 7–9, February 22, 2022. Notes: Components may not add to total due to rounding. Data are preliminary and may be revised.*

1.3 Federal funding of R&D expenditures

Over the long term, the federal funding in R&D (in constant 2012 dollars) has grown by 60% in 20 years (i.e. **2.3% per year**), while US GDP has increased (in constant 2015 dollars) from $13.75 trillion to $20.53 trillion (i.e. 2.05% per year) (see figure 3). In the meantime, R&D spending in the USA rose from $269 billion to $668 billion, an annual increase of **4.9%**.[3]

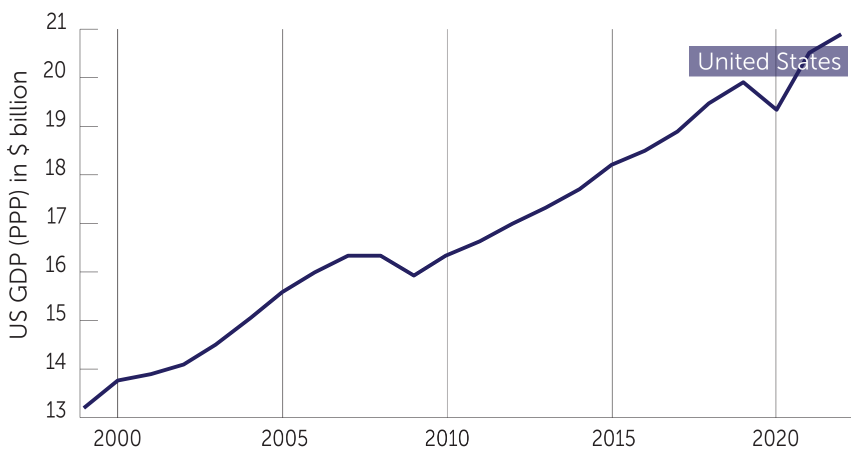


Figure 3: Evolution of US GDP (PPP $ billion) Source: Worldbank database, Consulted by Tematys.

The following data by agency are taken from the source https://ncses.nsf.gov/surveys/federal-funds-research-development/.

The contribution to the federal government's R&D budget will be $148 billion in 2020, rising significantly to $195 billion in 2023. The 21/22/23 figures have not yet been adjusted for inflation. The average annual increase of 9.5% is therefore considered an inflation-linked budget increase.

[3] Source https://ncses.nsf.gov/pubs/nsf22314

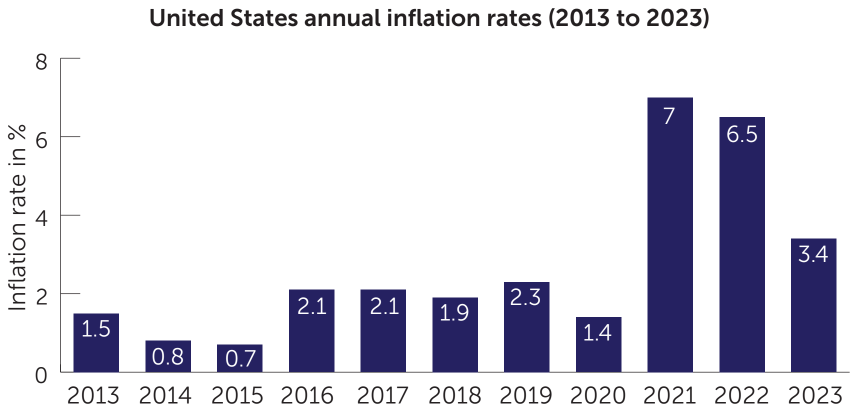


Figure 4: US Inflation Rate 2013–2023.
Source: www.usinflationcalculator.com/inflation/current-inflation-rates/

	FY 2020 (real)	FY 2021 (real)	FY 2022 (real)	FY 2023 (est)	Change 22–23 (%)
Department of Defense (DoD)*	65.165	70.079	79.108	92.583	+17%
Department of Health and Human Services (DHH)	42.226	42.226	44.706	46.643	+4.3%
Department of Energy (DoE)		17.788	20.085	21.983	+9.4%
NASA		12.176	13.865	12.878	-7.1%
National Science Foundation (NSF)	6.277	7.515	7.158	7.918	+10.6%
Department of Agriculture		3.031	3.185	3.420	+7.4%
Department of Commerce		2.099	2.339	2.528	+8.1%
All others		5.810	6.516	7.216	+10.7%
TOTAL ($ billion)	147.946	160.724	176.692	195.170	+10.4%

*includes Defence Dept, NNSA, FBI & DHS CISA

Table 3: Estimated R&D in FY 2023 Appropriations by agency (budget authority in $ billion).
Source: Data of the Congressional Research Service, website visited on 31/10/2023

Federal expenditures increased from $148 billion in 2020 to an estimated $195 billion in 2023. The federal government continues to be an important source of support for all R&D-performing sectors and remains the largest funder of basic research. The share of federally funded R&D, however, has been on a path of decline since 2010 (from 31% in 2010 to 19% in 2020). The share of federally funded basic research has also consistently declined (from 52% in 2010 to 41% in 2019).

These declines stem, in part, naturally from the large increases in R&D funding and performance by the business sector in recent years. This trend, however, indicates that federal funding has not kept up with the increases in other sectors.

2. Methodology & main results

The scope of the study concerns the financing of R&D in photonics by the US federal government via the grants system. Contracts are not included in our study.

Among the numerous federal agencies, we first identified the five largest (Defence, Health, Energy, NASA, NSF). These five agencies alone account for 93.3% of the federal budget for R&D expenditure.

We searched the grant databases of these different agencies. The information for two databases (NIH and NASA) was not sufficient for our extraction method. We, therefore, extracted information from three grant databases (DoD, DoE, NSF) for the years 2021 and 2022. When the information was available, it was in the first few months of 2023. These three agencies represent 60.2% of the federal R&D budget.

For 2022, we identified a funding volume covering photonics themes of $1.23 trillion, corresponding to 9.4% of the initial sample (federal grants only). The expected growth for 2023 is 20%, which is in line with the GBARD increase[4].

DoD grants will account for 12.2% of DoD R&D spending in 2022 ($9.7 billion out of $79.108 billion). We did not find a rate for the other agencies. As the DoD represents a large proportion of our sample, we have used this rate of 12.2% for the sample. We, therefore, started with an initial sample of $13.12 billion, covering DoD, DoE and NSF grants. We then extracted the photonics-funded projects from these databases, using the same method we have been using for the last eight years to analyse the databases of European programmes, i.e.

- Identification and extraction of projects using 40 keywords representative of all photonics fields.
- Manual data cleaning, removing irrelevant projects and false positives.

Across the agencies, SBIR programmes form the backbone of support for SMEs. We have therefore extracted from the US SBIR database, using the same methodology as above, the full list of photonics projects carried out by SMEs. Finally, using all of these databases, we have carried out an analysis

- by agency and by year of the distribution of subsidies to photonics players,
- by the intensity of photonics in the grants, i.e. the number of projects selected within the photonics perimeter out of all the projects selected by the agency.

[4] These recent figures have not been restated for inflation.

3. Detailed analysis per agency

3.1 Department of Defense (DoD)

The DoD budget has been growing since 2015 from $497 billion to $742 billion. This budget covers DoD contract obligations, payroll spending, and grant awards in the 50 states and the District of Columbia.

It is almost 2.2% of the country's gross domestic product. Of those funds, $9.7 billion were awarded as grants (see Table 4).

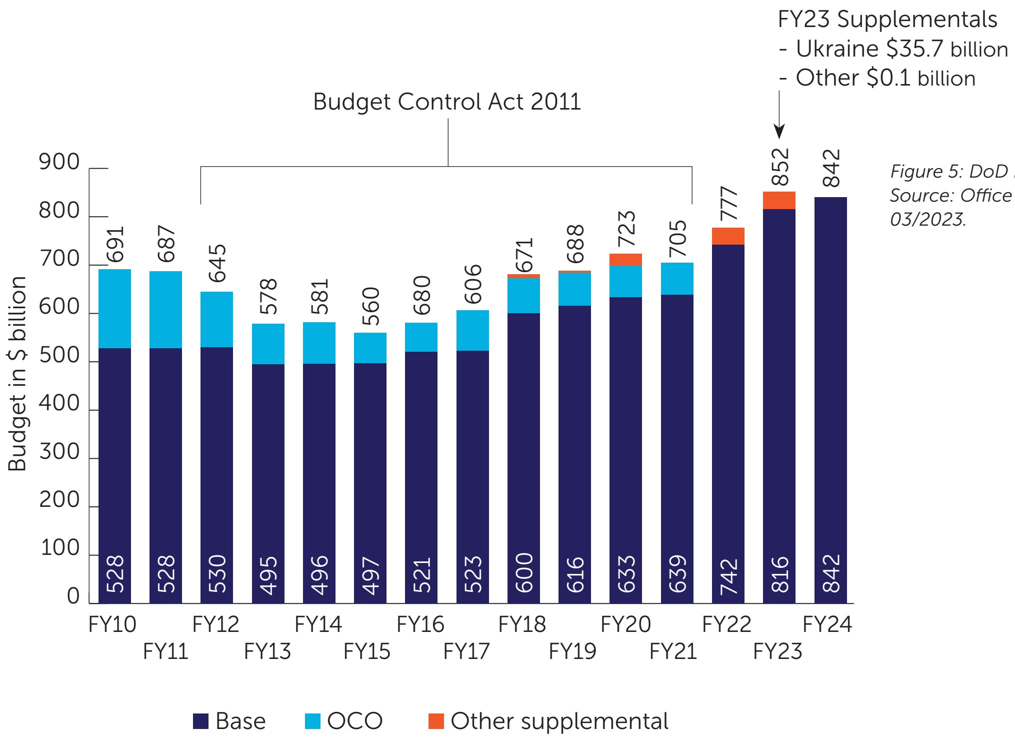


Figure 5: DoD Budget FY 2010 – FY 2024.
Source: Office of the USD Comptroller/CFO, 03/2023.

	Total	Photonics	%	Method
DoD award to lab	$3.1 billion	$0.144 billion	4.6	DoD Database extraction
DoD SBIR	$2.09 billion	$0.201 billion	9.6	SBIR database extraction
DoD grants to other companies	$4.5 billion	$0.299 billion	6.6	Estimation
Total	$9.7 billion	$0.644 billion		

*includes Defence Dept, NNSA, FBI & DHS CISA

Table 4: Intensity of Photonics in DoD Grants (2022).
Source: US database, treatment by TEMATYS.

3.2 National Science Foundation (NSF)

Funding for photonics projects within the NSF increased significantly from 5.2% of projects (or 4.6% of budgets) in 2020 to 6.9% of projects (or 8.5% of budgets) in 2022. This may be linked to programmes linked to the Chips Act (at the federal level) and AIM Photonics (at the regional and federal level). Both are putting a major effort back into semiconductor and optoelectronic materials and components.[5]

Future data will be instructive to see if this significant growth is consolidated over time.

3.3 DARPA

Based on pluriannual programme funding, photonics funding in DARPA is strongly growing from $72 million to $168.7 million (2.2% to 4.2% of global DARPA funding) between 2021 and 2023 (see table 5). DARPA programmes closely linked to Photonics are displayed in Table 6.

Table 5: Photonics part in global DARPA funding. Source: DARPA Agency, Treatment by TEMATYS.

Yearly funding per agency	2021	2022	2023
DARPA funding per year ($ million)	3,304.781	3,769.405	4,017.689
Photonics part	2.2%	2.7%	4.2%

Considering the forecast of programmes in years 24–27, the growth should be slower in the next years.

[5] Source NSF Database, treatment by TEMATYS

Budget of photonics programmes in DARPA multiannual programmes

	FY2021	FY2022	FY2023 base	FY2023 total	FY2024	FY2025	FY2026	FY2027
ES 01 – Electronic Science	28,681	16,361	17,645	17,645	29,153	34,178	52,200	52,410
Atomic photonic integration	14,681	9,361	9,000					
ES 02 – Beyond scaling science	57,365	65,145	70,188	70,188	58,923	58,940	43,250	53,540
Joint University Microelectronics programme 2.0			18,000					
ELT01 – Electronic technologies	113,633	160,891	136,744	136,744	143,985	142,536	139,622	146,872
Focal arrays for curved infrared imagers (FOCll)	19,000	21,750	12,139					
Generating RF with photonics for low noise (GRYPHON)		17,000	21,000					
Compact high intensity radiating photonics (CHIRP)		12,000	12,605					
Lasers for universal microscale optical systems (LUMOS)	21,000	23,000	18,000					
ELT02 – Beyond scaling technologies	194,158	232,493	421,001	421,001	427,077	423,210	447,524	440,024
Next generation microelectronics – advanced manufacturing approaches for three-dimensional heterogeneous integration			60,000					
Mixed technology integration	16,701	27,854	33,406	33,406	89,030	105,175	112,332	120,832
Reconfigurable imaging (Relmagine)	6,000	6,000						
Modular efficient laser technology (MELT)			12,406					
Precise robust intertial guidance for munitions (PRIGM)	2,000							
Beyond scaling advanced technologies	76,288	112,862	217,511	217,511	224,000	227,850	223,736	225,936
Photonics in the package for extreme scalability (PIPES)	11,000	13,000	5,000					
Total DARPA photonics	73,681	102,111	168,150	168,150	179,851	183,499	188,453	192,329
Total programme lies	486,826	615,606	896,495	896,495	972,168	991,889	1,081,644	1,039,614
% Photonic	15.1%	16.6%	18.8%		18.5%	18.5%	18.5%	18.5%

Table 6: Photonics programmes in DARPA multiannual programmes. Source: DARPA Agency, Treatment by TEMATYS.

Among them, four programmes are over $30 million US funding in the 21–23 period.

- **Lasers for Universal Microscale Optical Systems LUMOS: 62M**
  The LUMOS programme integrates high-performance light sources into silicon-integrated photonics, enabling compact, rugged, high-performance systems for positioning, navigation, communications, 3D imaging, and quantum technologies. LUMOS will deliver the missing capability to provide compact optical sources at wavelengths from the visible to the infrared and will create a universal manufacturing platform that builds upon the current photonics ecosystem.

- **Focal Arrays for Curved Infrared Imagers: FOCII 52M**
  The FOCII programme is developing curved focal plane arrays for broadband infrared (IR) images to enhance battlefield detection and discrimination while maintaining situational awareness. This programme will create novel designs for IR imagers that enable minimal size, weight and cost for size-constrained applications. This will allow new applications in passive seeker technology for missiles, overhead persistent infrared imaging, 360-degree situational awareness, infrared search and track, and long-range targeting.

- **Generating RF with Photonic Oscillators for Low Noise: GRYPHON**
  The Generating RF with Photonic Oscillators for Low Noise (GRYPHON) programme seeks to develop compact microwave frequency oscillators with extremely low phase noise to enable advanced sensing and communication applications. In the last decade, major advances in oscillator performance have been realised using optical techniques to synthesise high-fidelity microwave signals. Such oscillators employ optical frequency division to reach world-record phase noise levels. The solutions demonstrated to date, however, have sacrificed other important attributes in pursuit of spectral purity. Such trade-offs are problematic because module size, cost, tunability, and environmental sensitivity are also critical factors that determine the applicability of microwave sources to commercial and military systems.

  GRYPHON will leverage recent developments in nonlinear photonics and photonic-electronic integration to develop microwave sources with noise performance that meets or exceeds that of the best discrete oscillator modules yet occupy a compact volume typical of far noisier chip-scale voltage-controlled oscillators (VCOs). Moreover, by the programme's end, GRYPHON microwave sources will operate as synthesisers with the ability to tune to any frequency from 1 to 40+ GHz during operation. This combination of features is unprecedented in today's state of the art. It will establish a new regime of source technology that is expected to transform the types and capabilities of military and commercial radar and communication systems.

- **Atomic-Photonic Integration: A-PhI $33 million**
  The a-Phi programme reduces the size, weight, and power of atomic clocks and gyroscopes for position, navigation, and timing (PNT) applications through the development of integrated photonics. Specifically, A-PhI will demonstrate that a compact photonic integrated chip can replace the optical assembly for trapped atomic gyroscopes and clocks without degrading the performance of the device.

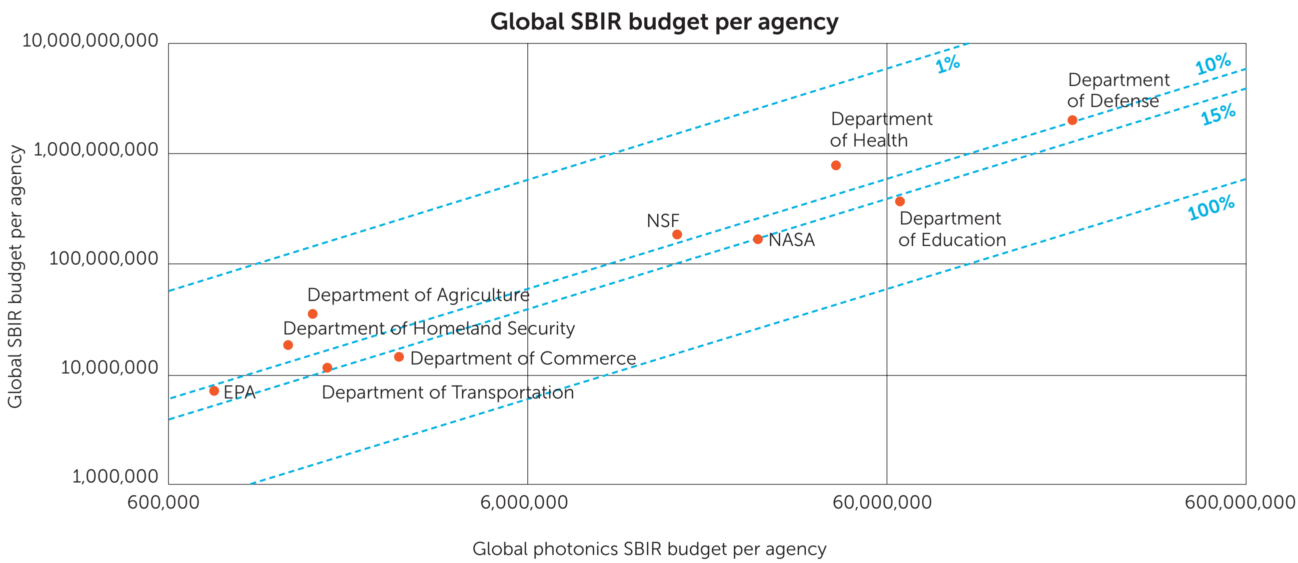
3.4 SBIR programme analysis

Among the 20,761 projects in the SBIR database, we have identified 2,259 projects dealing with Photonics over the three years 2020–2021–2022 (see Table 7).

	2020	2021	2022
Total SBIR project in database	7,309	6,872	6,580
SBIR Photonics projects	848	732	679
Total SBIR Budget in database ($ million)	3,902.36	3,612.8	3,733.66
SBIR Photonics budget ($ million)	404.05	360.14	362
% photonics project	11.6	10.7	10.3
% photonics budget	10.4	10	9.7

Table 7: Evolution of Photonics funding in SBIR-funded project.
Source SBIR database, Treatment by TEMATYS.

Throughout the analysis (2020-2022), the share of photonics projects has remained stable, representing 10.9% of projects and 10% of budgets.



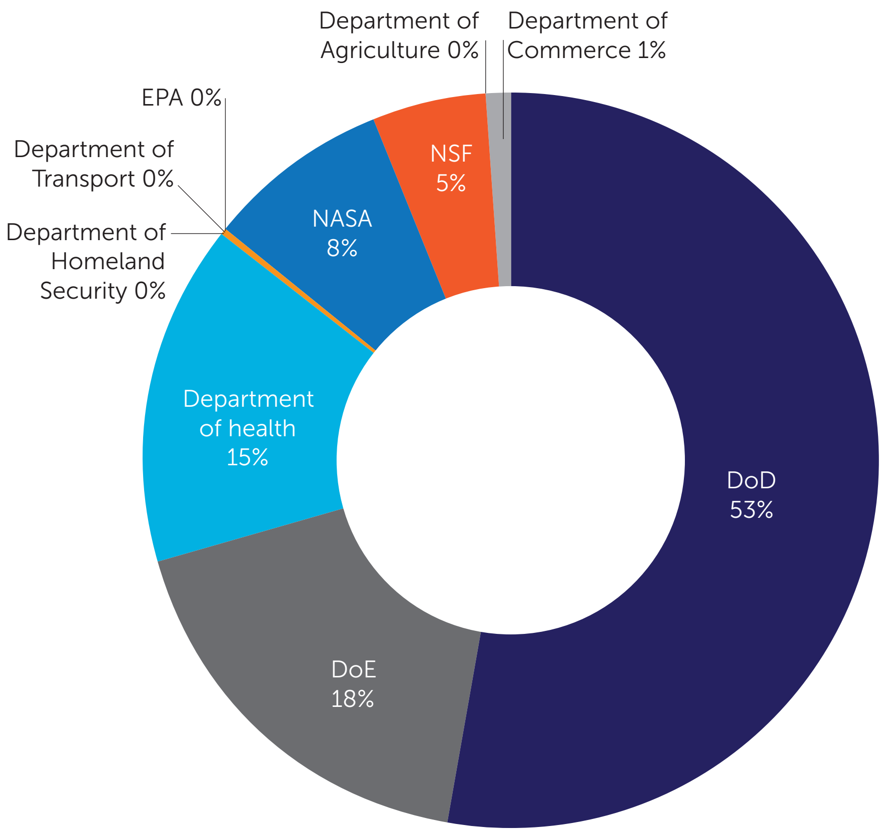
	2022 (total SBIR)	2022 (photonics SBIR)
Department of Agriculture	34,404,060	1,513,565
Department of Commerce	14,209,275	2,667,186
Department of Defense	2,089,007,187	200,596,779
Department of Education	371,283,493	66,308,768
Department of Health	782,471,477	44,194,773
Department of Homeland Security	18,215,695	1,298,248
Department of Transportation	11,519,638	1,649,905
EPA	6,889,465	799,866
NASA	168,860,387	26,673,254
NSF	184,769,830	16,048,069

Figure 6: Intensity of SBIR Photonics-funded project by funding agency (2022).
Source: Tematys/Photonics21, 2023.

In 2022, five agencies (DoD, DoE, DHH, NASA, NSF) funded 92% of all SBIRs. Of these, NASA and the DoE have the highest photonics intensity (more than 15% of the budgets allocated via the SBIR tool have funded photonics projects). Conversely, the Department of Health is well below the average (10%) at 5.6%.

Unsurprisingly, the DoD, which accounts for 53% of SBIR funding, is close to the average funding (10%).

Figure 7: Breakdown of Photonics funding in SBIR database (2022) by agency. Source: Tematys/Photonics21, 2023.



4. Conclusions

Throughout 2021–2022, funding for photonics projects in the agencies (DoD, DoE, NSF) and SBIR amounted to around $1.25 billion, stable. The databases available for 2023, the DARPA multi-year programmes and the evolution of DoD funding allow us to estimate growth in 2023 to $1.6 billion. This growth is in line with that of GBARD. This financing is mainly driven by defence applications (DARPA and DoD) (60% of federal funding).

	2021	2022	2023
DARPA (Defence R&D)	73.68	102.11	168.15
DoD (Grants to Labs)	162.69	144.78	90.89
DoD SBIR (Start-up & SMEs)	185.01	200.60	
DoD other awards (larger companies)	300 (estimate)	299.50 (estimate)	
NSF SBIR	15.26	16.05	
NSF (Independent)	311.13	260.47	309.80
ARPA-E (Environment)	42.21	43.02	42.00
SBIR (not DoD or NSF)	175.13	161.40	
Total photonics grants ($ million)	1,265.11	1,227.94	1,597 (est.)

Table 8: Evolution of federal funding for photonics project (21–23) – in $ million US. Source: Tematys/Photonics21, 2023.

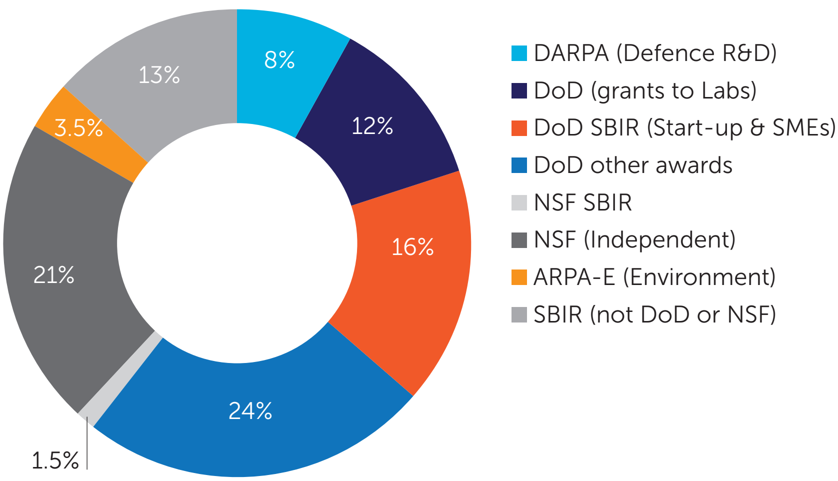


Figure 8: Breakdown (defence in red/civil in blue) of the $1.23 billion photonics federal funding in 2022. Source: Tematys/Photonics21, 2023.

Including federal and regional funding, US Photonics grants were worth $1.4 billion in 2022 and estimated to be $1.7 billion in 2023.

In addition to these federal grants, we also examined regional funding. The largest programme in the "Manufacturing Initiative" launched in 2014 is AIM Photonics, which has received $934 million in funding between 2015 and 2022 over the seven years of its existence, i.e. $130 million per year.

AIM Photonics is one of nine manufacturing innovation institutes (MIIs) established by the United States Department of Defense. The DoD MIIs bring new technologies to life with federal taxpayer dollars combined with matching funds from academia, industry, and state governments, building a national network of public-private partnerships and creating an industrial common for manufacturing R&D, as well as workforce education and development.

On 29 September 2021, the Department of Defense (DoD) awarded a $32 million, 7-year cooperative agreement to the Research Foundation for the State University of New York (RF SUNY) to continue its role leading the American Institute for Manufacturing Integrated Photonics (AIM Photonics). AIM Photonics, headquartered at the Albany NanoTech Complex in New York, will continue to collaborate with public and private entities to advance US leadership in manufacturing integrated photonic circuits. In support of this follow-on assistance agreement, $165 million in federal funding will be combined with over $156 million in non-federal cost-share from companies, colleges and universities, and state and local governments[6]. This funding consolidates annual funding over the long term of between $110 million and $130 million per year.

[6] www.dodmantech.mil/About-Us/Manufacturing-Innovation-Institutes-MIIs/AIM-Photonics

5. Annex

5.1 Annex 1: NIST analysis (funded by the department of commerce)

In the PML brochure[7], 15 out of 41 groups are clearly photonics partners of JILA. According to the US Court of Auditors, NIST employs a total of 3,400 people.[8]

The distribution of scientific and technical posts is as follows: PML = 40.5% of the scientific staff. If we consider that photonics accounts for 15/41 of PML, this corresponds to 14.8%.

Source of following figures: www.gao.gov/assets/gao-23-105521.pdf

- Global NIST: 3,400 employees.
- Photonics in NIST
  - Raw Source: www.nist.gov/system/files/documents/2022/01/21/pml-brochure.pdf
  - PML Scientific & technicians about 40.5% of total NIST technical staff
  - 15 scientific groups over 41 in PML working in the Photonics field (36.5%)
  - Leading to Total Photonics staff in NIST: 14.8%

- NIST core research account, scientific and technical services rose 9% in 2023, from $853 million to $930 million.
  - ww2.aip.org/fyi/2023/fy23-budget-outcomes-nist
  - Leading to $126 million for photonics staff in NIST in 2022

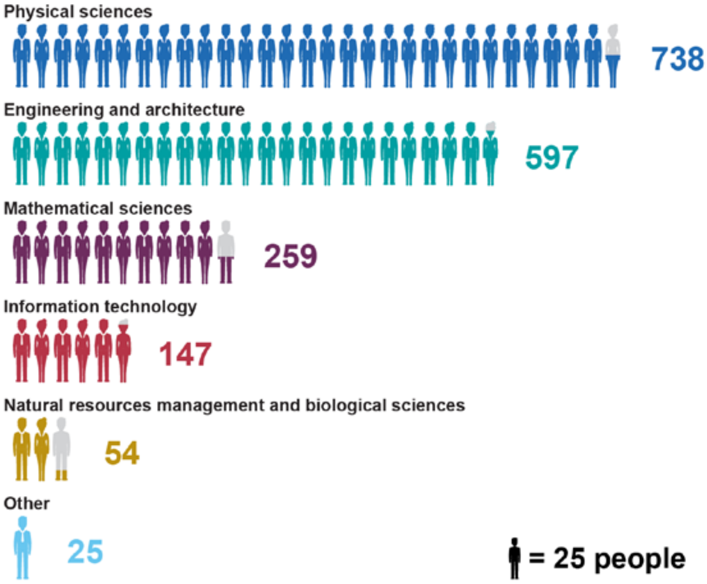


Figure 9: Scientific and Technical Occupational Groups at NIST.
Source: National Institute of Standards and Technology, Improved Workforce Planning Needed to Address Recruitment and Retention Challenges, 2023, GAO-23-105521, NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY: Improved Workforce Planning Needed to Address Recruitment and Retention Challenges, p. 5.

[7] www.nist.gov/system/files/documents/2022/01/21/pml-brochure.pdf
[8] www.gao.gov/products/gao-23-105521

5.2 Annex 2: Photonics in Navy research labs (NRL)

Optical Science Division of the Naval Research Laboratory (NRL) is seeking proposals for innovative research supporting ongoing programmes within the Optical Sciences Division related to a wide variety of topics in the following areas[9]:

1) The development of countermeasures against laser-guided or laser-aided threats, such as laser beamrider missiles, laser designators, and laser rangefinders. Of these, laser beamriders are the highest priority threat. Innovative new techniques which support laser countermeasures are desired.

2) The development of countermeasure technology and countermeasure techniques against advanced anti-air and anti-ship imaging infrared seekers. NRL is interested in organisations with a strong knowledge of imaging tracker design and processing to conduct countermeasure research. Offerors must also have a background in the use of modelling and simulation tools for imaging seekers to conduct countermeasure research.

3) Fabrication of optical fibres that transmit infrared (IR) radiation, especially chalcogenide and heavy-metal oxide glass fibres; processing techniques for making IR fibres; purification of glass starting materials; novel crucible fibre drawing techniques; speciality fibres for chemical sensor applications and techniques for making chemical sensors. Development of ruggedised, vibration-resistant and athermal cables and connectors for middle wavelength IR (MWIR) fibres for use with high-power mid-IR lasers. New technologies for making IR fibre switches work with mid-IR lasers, as well as technology for the fabrication of IR fibre couplers, filters, and splitters, are needed.

4) Fabrication of domes, aspherical optics and large ($\geq$ 20 inches) diameter windows with high transmission across UV-visible and infrared wavelengths. Technologies that utilise environmentally rugged materials (glasses, ceramics or poly/single crystals) and produce defect-free optics with wide-band anti-reflection coatings are sought.

5) New and advanced technology for making highly efficient, thin film photovoltaic devices. Areas of interest include new absorber materials, earth-abundant materials, and technologies enabling thin film-based multi-junction devices. In addition, innovative techniques to form flexible devices by depositing these films on flexible polymer or metal substrates are required.

6) Fiber optic sensors for detecting acoustic, magnetic and electric fields, rotation rate, strain, temperature, pressure, chemical, and other parameters. Novel interrogation, multiplexing, demultiplexing and modulation/demodulation techniques using frequency, wavelength and time division, or other methods to increase sensor count per fibre, decrease electronic demodulation power requirements, and provide all-optical signal processing, and lower total system cost are desired. In addition, methods are sought to improve fibre sensor performance, packaging, deployment, and survivability of these systems in a variety of environments. Low-phase noise laser sources that feature very good isolation from ambient effects to improve overall optical system performance are desired. Low power, high bandwidth, and signal-

[9] www.nrl.navy.mil/Portals/38/PDF%20Files/FY23_BAA_Announcement_FINAL.pdf?ver=MrQ00MLWw9moImdKNEPI3g%3d%3d

processing components with automatic signal detection to fill current technology gaps for autonomous sensors are of interest. Robust, agile, advanced automation tools that are able to detect, classify and track selected targets of interest acoustically, using data from fixed and mobile arrays and generating automated contact reports are desired to reduce workforce requirements associated with sonar operator tasks.

7) High-frequency data transfer networks using fibre optics; signal processing in fibre optic links; optical-microwave delay lines for gigahertz signal transmission, high frequency directly modulated diodes and external modulators, and high-speed detectors (particularly any aforementioned device that reduces delay line loss). Fibre devices such as amplifiers, fibre lasers, super-luminescent fibres, and phase shifters; laser diodes that meet military specifications and can operate in the multigigabit/s range; harmonic generation and mixing using laser diodes; nonlinear effects that impact fibre optic links such as soliton propagation, Brillouin scattering, and four-wave mixing. Integrated optical devices for sensors, optical-microwave delay lines, signal processing, networks, and digital or analogue communication links.

8) Glass and processing techniques for nanochannel glass technology and holey fibres; speciality glasses and fibres for sensor applications and nuclear radiation hardness; glass and processing techniques for microwire glass technology; optical fibres with high mechanical strength, survivable coatings, and low bending loss. Novel nonlinear optical materials for optical limiters and switches to protect eyes and sensors against intense laser radiation; photonic band-gap materials; optical properties of materials and coatings; narrow band gap superlattices; quantum wells, wires and dots; bioconjugated quantum dots to probe cellular and environmental behaviour; novel nanostructures; the interaction of light with single microdroplets; development of real-time in-situ optical instrumentation to detect bioaerosols, including single particles on-the-fly; development of type II "W" mid-IR lasers and quantum cascade lasers; other MWIR laser and amplifier devices that increase brightness and power; organic light emitting sources and optoelectronics; slow light studies; non-linear optical probes such as Fast CARS; and development of condition based sensors for oil debris monitoring.

9) Electro-optical, visible, infrared, multi spectral and hyperspectral technologies used in systems for reconnaissance and surveillance of air, ocean, and ground targets, from space, air, surface and subsurface platforms; high-speed digital optical/RF communications in a tactical environment, including architectural issues; algorithmic development, including digital image and signal processing algorithms for target detection and tracking; the measurement and theory of optical signatures of air and ocean targets; the acquisition, and characterisation and simulation of large-area background imagery; atmospheric propagation effects relevant to missile warning, laser counter-measures, and imaging; electro-optical sensor technology including efficient high-speed photo-detectors, focal plane arrays and signal processing; electro-optical components; digital holography and electronic shutters; signal processing and data compression for multi-colour electro-optical and infrared sensors; multi sensor/data fusion and exploitation; neural network processing and electronics particularly applicable to electro-optical sensors; advanced data compression techniques and electronics for very large area visible, infrared, and multi spectral; pulsed solid state blue-green lasers.

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