



Exploration of photonics markets

EXTRACT

METAMATERIALS & METASURFACES FOR OPTICS AND RF

MARKET, TECHNOLOGIES AND TRENDS



Primarily mysterious concepts of Metamaterials & Metasurfaces have been transformed to first civil applications and now they are being developed rapidly to revolutionize Optics and RF markets

Reference: R202401-026

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1 INTRODUCTION

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Report's Objectives

- Overview of the significant research in the area of Metamaterials (MM) and Metasurfaces (MS)
- Statistics on currently funded projects and recently submitted patents
- Key players description
- Revenue of the Metamaterials and Metasurfaces markets at the level of components and modules
- Market forecasts up to 2029
- Comprehensive overview of Metamaterial and Metasurface products at the component and module level
- Review of currently tested or potentially attractive applications based on Metamaterials and Metasurfaces
- Identification of challenges and bottlenecks for the broader adoption of MMs and MSs in large volume applications



Information sources and methodology

- Tematys' in-house knowledge of Metamaterials technology and players.
- Financial and business information on over 30 commercial companies of the Metamaterials market.



- Interviews with key manufacturers of MMs and MSs.



- Bibliographic research.



- Attendance at international conferences in the field of Metamaterials.





What you will FIND and NOT FIND in this report



INCLUDED

In the report

- Photonic and RF **Metamaterials** and **Metasurfaces** technology analysis.
- Detailed market data and forecasts on **Metamaterials** and **Metasurfaces**.
- Description of products based on **Metamaterials** and **Metasurfaces** designed for **OPTICAL** and **RF** applications.
- Review of the concepts for **future Metamaterial usage**.



NOT INCLUDED

In the report

- Detailed analysis of Metamaterials and Metasurfaces for **ACOUSTICS**, **MAGNETICS** and **MECHANICS** markets.
- Detailed description of **RESEARCH**, **SPACE** and **MILITARY** applications.
- Detailed description of competitive technologies.
- Detailed description of MM and MS manufacturing processes



List of abbreviations

5G	Fifth Generation	IoT	Internet of Things
6G	Sixth Generation	IR	Infrared
ADAS	Advanced Driver Assistance System	IRS	Intelligent Reflective Surface
AI	Artificial Intelligence	ITU	International Telecommunication Union
AR	Augmented Reality	LED	Light Emitting Diode
BA	Beamforming Antenna	LiDAR	Light Detection and Ranging
BS	Base Station	MCU	Microcontroller Unit
CAGR	Compound Annual Growth Rate	MIMO	Multiple-Input Multiple-Output
CMOS	Complementary Metal Oxide Semiconductor	MM	Metamaterial
DPS	Double Positive Material	mmWave	Millimeter wave
eMBB	Enhanced Mobile Broadband	MR	Mixed Reality
EM	Electromagnetic	MS	Metasurface
ENG	Epsilon Negative (material)	RF	Radio Frequency
ENZ	Epsilon Near Zero (material)	RIS	Reconfigurable Intelligent Surface
EO	Electro-Optic	THz	Terahertz
FDD	Frequency Division Duplex	VR	Virtual Reality
GPS	Global Positioning System	XR	Extended Reality



Definitions

Metamaterial (MM)
for Optics and RF

Bulk (3D) nanostructured material with unusual electromagnetic properties which unit cell size a is smaller than the wavelength λ ($a < \lambda$)

Metasurface (MS)
for Optics and RF

Surface (2D) nanostructured material with unusual electromagnetic properties which unit cell size a is smaller than the wavelength λ ($a < \lambda$)

Metalens

Flat lens that uses metasurface to focus light like a lens

Metamaterial antenna

Type of antenna which uses metamaterials to increase performance or miniaturize a typical radio waves emitter/receiver

Beamforming

Focusing the radiated energy on separate targets without illuminating adjacent users

Beam steering

Changing the direction of the main lobe of a radiation pattern

Beam switching

Effective user tracking by switching to different beams while endpoint moves

Reconfigurable Intelligent Surface (RIS)

Programmable structure that can be used to control the propagation of radio waves, mainly intended to extend the range of antennas at lower cost

6G

Sixth generation communication standard, planned successor to 5G, likely to be significantly faster and to support applications beyond current mobile use scenarios

AR/VR/MR/XR

All real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables



List of Companies mentioned in the report

Metamaterials and Metasurfaces manufacturers: Anywaves, Carillon Technologies, Echodyne, Evolv Technology, Gapwaves AB, Greenerwave, Huawei Technologies, Kuang-Chi Group, Kymeta Corporation, Lumotive, Metalenz, MetaPower, Metawave Corporation, NIL Technology (NILT), Pivotal Commware, Acree Technologies Incorporated, Antrum Ltd, appliedEM innovations, BlueHalo, Fractal Antenna Systems, Isotropic Systems, JEM Engineering, LongWave Photonics, Meta Material Inc., Metaboards, Metaccept, Metamagnetics Inc., Moxtek, Multiwave Technologies AG, Nano-Meta Technologies, Nanohmics, Notch Inc., Phoebus Optoelectronics, Physical Sciences Inc., Plasmonics Inc., Radi-Cool, Sensormetrix, SI2 Technologies, TeraView, Tesla Dynamic Coils BV, Tunoptix, Ultimetas, Vadient Optics, Wave Up

Companies conducting research on Metamaterials and Metasurfaces: 3M, Alcatel-Lucent, Analog Devices, Applied Materials, BOE Technology Group, Brainware Terahertz Information Tech, Brelyon Inc., Chengdu XPHASED Technology, China Electronics Technology Group Corporation, Denki Kogyo Co., Ltd. (DKK), Ericsson, Essilor International, Facebook Tech, Globalfoundries, Goodix Technologies, Halliburton, Hangzhou Leon Dongxin Microelectronics, Hamamatsu Photonics, IBM, IEE SA, Infineon Technologies, Intel Corporation, iRay Technology, KT Corporation, LG Electronics, Lockheed Martin, Magic Leap, Microsoft, Mitsubishi, Northrop Grumman, PSA Automobiles, Qualcomm, SAMSUNG, Samtec, Saudi Aramco, Seagate Technology, Seeing Machine, Sensirion AG, Shenzhen Lochn Optics Technology, Shenzhen Xinfeng Wei Ye Technology, Shenzhen Sunway Communication, Skyworks Solutions, Speedylink Technology, STMicroelectronics, Sunny Optical Technology, Suzhou Maswell Communication Technology, Swiftlink Technologies, THALES, Wuhan Mindsemi Co Ltd, Xerox PARC, Ziva Corporation etc.





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2 FROM “INVISIBLE CLOAK” CONCEPTS TO FIRST REAL APPLICATIONS

- ↳ Metamaterials for Optics and RF - what does it mean?
- ↳ Abundance of ideas and research
- ↳ From Defense, through RF to Optics



Beyond the natural limits

- Metamaterials or Metasurfaces use fine structural patterning to enable unusual optical, acoustic, mechanical or RF properties. They are made by combining and patterning standard materials. They can offer properties that do not exist in any bulk material or are unachievable in other ways, including, for example:
 - ❑ Zero or negative refractive index,
 - ❑ Extremely high reflectivity or absorption of specific frequencies,
 - ❑ Highly directional absorption or reflection spectra.
- Highly remarkable properties of some metamaterials (“acoustic cloaking”, “invisibility”) have caught the attention of mainstream media and many research centres around the world. The pursuit of designing and manufacturing such materials began in the 2000s and continues to the present.
- In the case of Metamaterials for Optics and RF, patterns manipulating the waves require structures that are generally smaller than the wavelength (size of nanostructures). This condition might become a challenge when designing meta-structures for VIS wavelengths, then they need to be the size of hundreds of nanometers or lower.

ADVANTAGES

- New functionalities
- System simplification, performance enhancement and miniaturization (e.g. by using flat optics)

CHALLENGES

- Design & simulation
- Low industrial maturity
- Size of structures for short wavelengths



Definition of Metamaterials & Metasurfaces

		MICRO/NANOSTRUCTURED MATERIALS (For Photonics & RF)	
		$a < \lambda$	$a \geq \lambda$
a - UNIT CELL SIZE	λ - GUIDED WAVELENGTH	WITH UNUSUAL PROPERTIES	W/O UNUSUAL PROPERTIES
3D	METAMATERIALS	<p>Examples in Photonics:</p> <ul style="list-style-type: none"> • Paints with micro/ nano pigments • Optically dense composites <p>Examples in RF:</p> <ul style="list-style-type: none"> • Radar absorbing composites 	<p>Examples in Photonics:</p> <ul style="list-style-type: none"> • Photonic Crystals • 3D diffusers
2D	METASURFACES	<p>Examples in Photonics:</p> <ul style="list-style-type: none"> • Dielectric mirrors • $\lambda/2$ or $\lambda/4$ plates • AR coatings <p>Examples in RF:</p> <ul style="list-style-type: none"> • Reflective grids in the front door of a microwave 	<p>Examples in Photonics:</p> <ul style="list-style-type: none"> • 2D Diffusers • Fresnel lenses • Diffraction gratings <p>Examples in RF:</p> <ul style="list-style-type: none"> • Frequency selective surfaces
1D	METAWAVEGUIDES	-	-



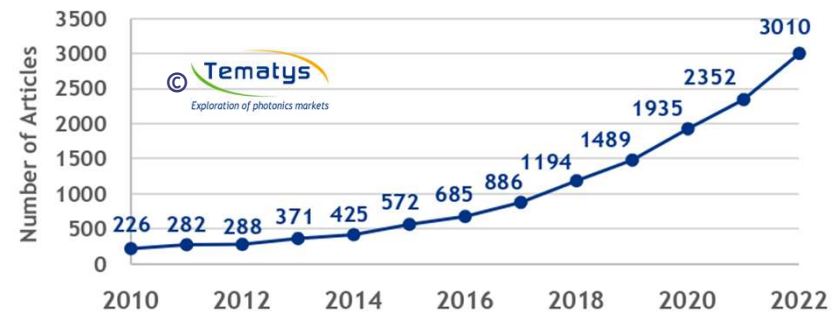
Adapted from: European Commission, Directorate-General for Research and Innovation, Nanostructured Metamaterials: exchange between experts in electromagnetics and material science, Baas, A. (editor), Scharf, T. (editor), Bergmaier, J. (editor), Kruglyak, V. (editor), Barois, P. (editor), Tretyakov, S. (editor), Publications Office, 2010, <https://data.europa.eu/doi/10.2777/54953>



Publications

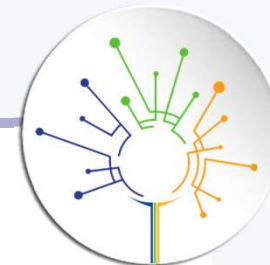
- The rapid progress in the field of metamaterials and metasurfaces has excited researchers far and wide. Indeed, metamaterials is a dynamic, worldwide research topic with over **25000** publications in the last two decades.
- The greatest metamaterial research growth is outside Europe, with **80%** of publications coming from **China** since 2015.
- China is pursuing a substantial research and development (R&D) effort in metamaterials.
- Functional nanomaterials and metamaterials were identified as priority areas of advanced materials in China's 13th 5-year plan, which calls for breakthroughs in core technologies, including new materials.
- This plan explicitly identifies metamaterials research, development, and application as a key area for science and technology innovation.

Number of articles per year since 2010 on *metamaterials OR metasurfaces* (Science Direct)



Number of articles per year since 2010 on *metamaterials OR metasurfaces* (PubMed)





Important role of defence applications

- Some prospects of metamaterial technology, such as invisibility cloaks or unprecedented vibration control, are very attractive to military customers (see the following table on the useful applications for defense).
- In fact, the development of metamaterials and metasurfaces is widely funded by EU, US and Chinese governments in numerous research programs (see slide 24). The innovations in defense and space drive the development of civil products. Also, many engineers working primarily for the military bring their experience to the civil market at a later stage of their careers (*analysis of the engineers' career path*).

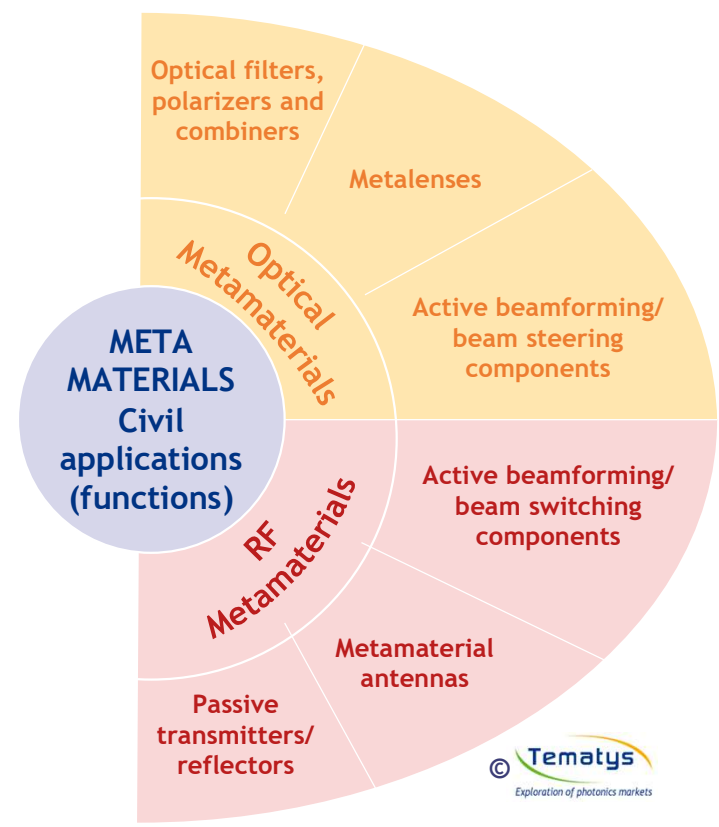
	TYPE OF MMs	LOW OBSERVABILITY	INNOVATIVE STRUCTURES	SENSING AND IMAGING	ENERGY MANAGEMENT
Optical	<ul style="list-style-type: none"> Thin coatings Flattening Low absorption 		Light controlling devices	<ul style="list-style-type: none"> Thin coatings Spectrometers and optical sensors Beam steering 	Resonators for low THz devices
RF	Thin films with resonators		Light beam absorbers	<ul style="list-style-type: none"> Smaller and/or better performance antennas Antennas substrates Beam steering 	Resonators for low THz devices
Mechanical			<ul style="list-style-type: none"> Protective armor Impact absorbers Low or no heat reflection 	Resonators for mechanical sensors	<ul style="list-style-type: none"> Resonators for energy harvesting Thermal insulators
Acoustic	<ul style="list-style-type: none"> Acoustic cloaking Low absorption Low absorption 		Light and/or thermal acoustic absorbers	Resonators for acoustic sensors	Resonators for low THz devices





First civil applications

- Although metamaterials and metasurfaces enable the creation of novel features that sound incredible or even magical ("invisibility"), much of the research around metamaterials is currently transformed to improve well-known optical and RF components and functions, used daily by millions of users around the world - mainly lenses and antennas.
- Due to the performance enhancement that metamaterials and metasurfaces can bring to the conventional systems in optics and RF, they are regarded as key elements of breaking disruption in these markets.
- In the case of optics, metamaterials have already made commercial inroads into tunable flat lenses, filters and combiners. They now find applications at the system level, in smartphones, cameras, cars, and gaming consoles.
- For the RF market, metamaterials targeting microwave frequencies have been successfully harnessed for wireless antenna technology for over a decade. At the system level, they are now entering 5G and 6G infrastructures, radars, IoT and security & safety devices.





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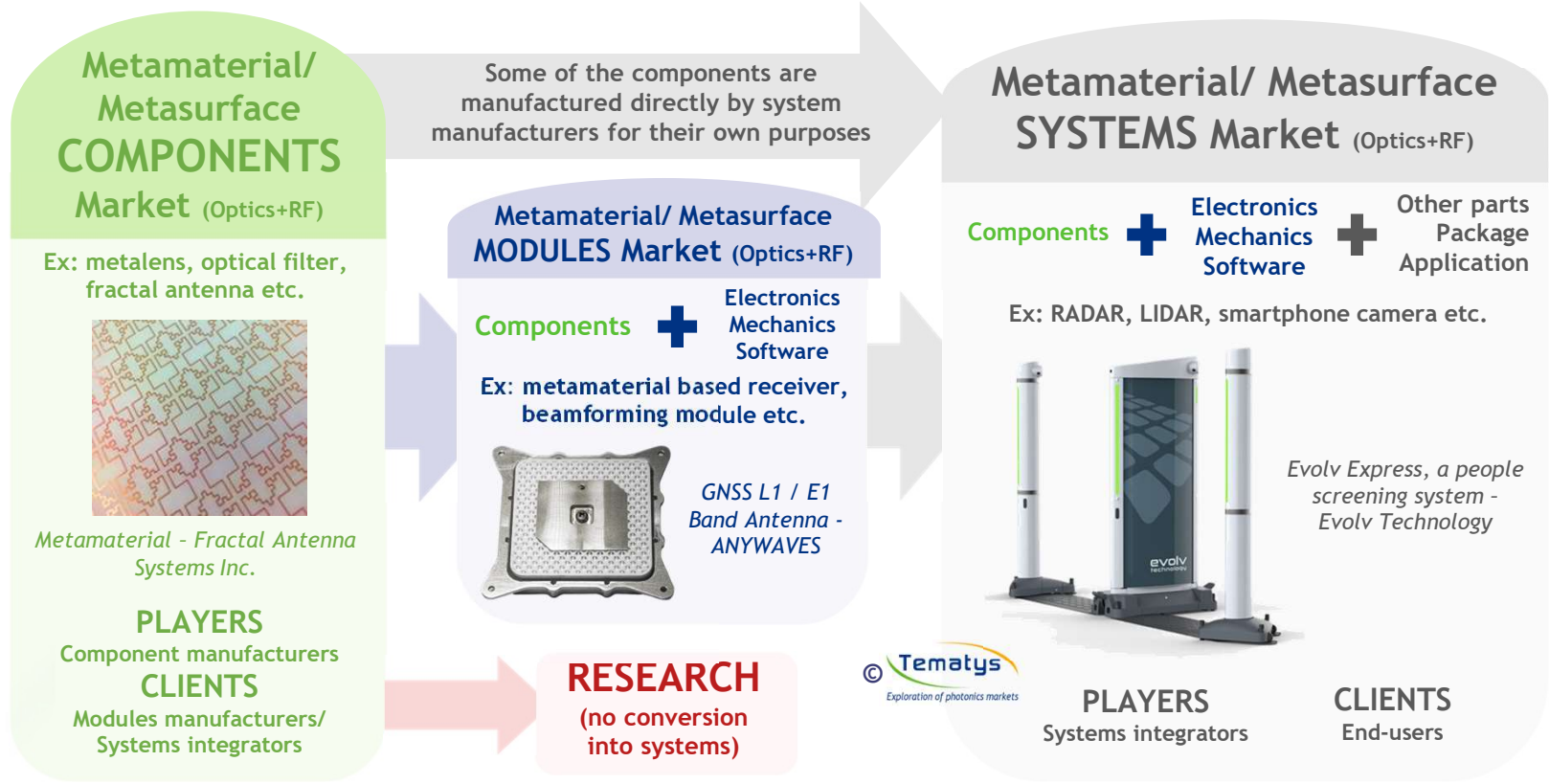
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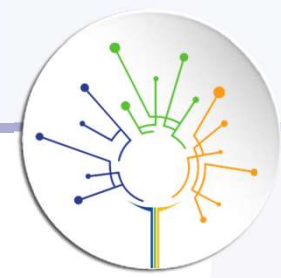
3 SMEs ARE OPENING THE MARKET

- ↳ Value chain
- ↳ Market data
- ↳ Funding and key partnerships
- ↳ Funded projects
- ↳ Patents
- ↳ Forecasts



From Components to Systems



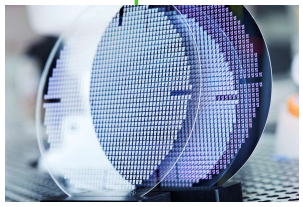
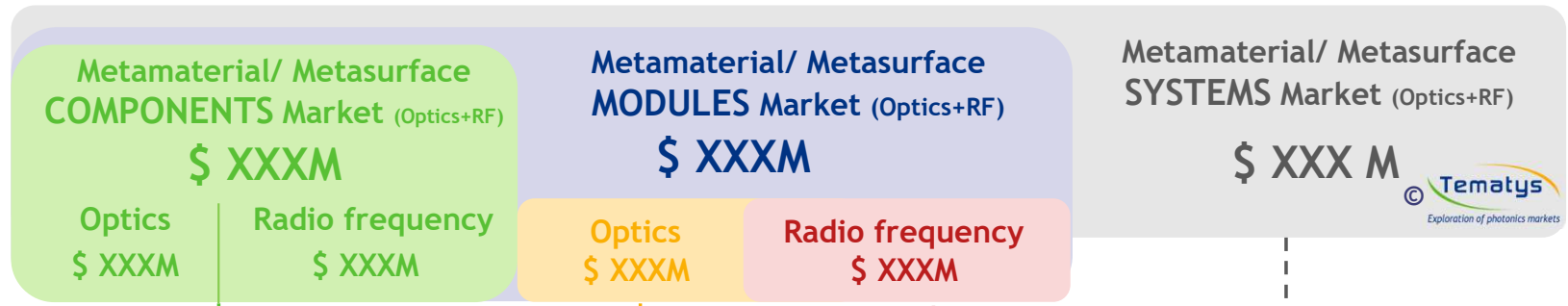


Worldwide market of Metamaterials & Metasurfaces 2022

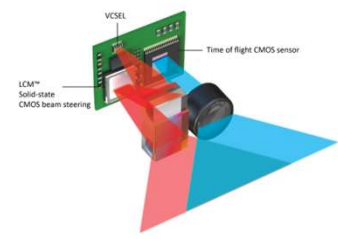
GENERAL ANALYSIS
In the report

DETAILED ANALYSIS
In the report

GENERAL ANALYSIS
In the report



Metalenses, NIL Technology



LIDAR module, Lumotive



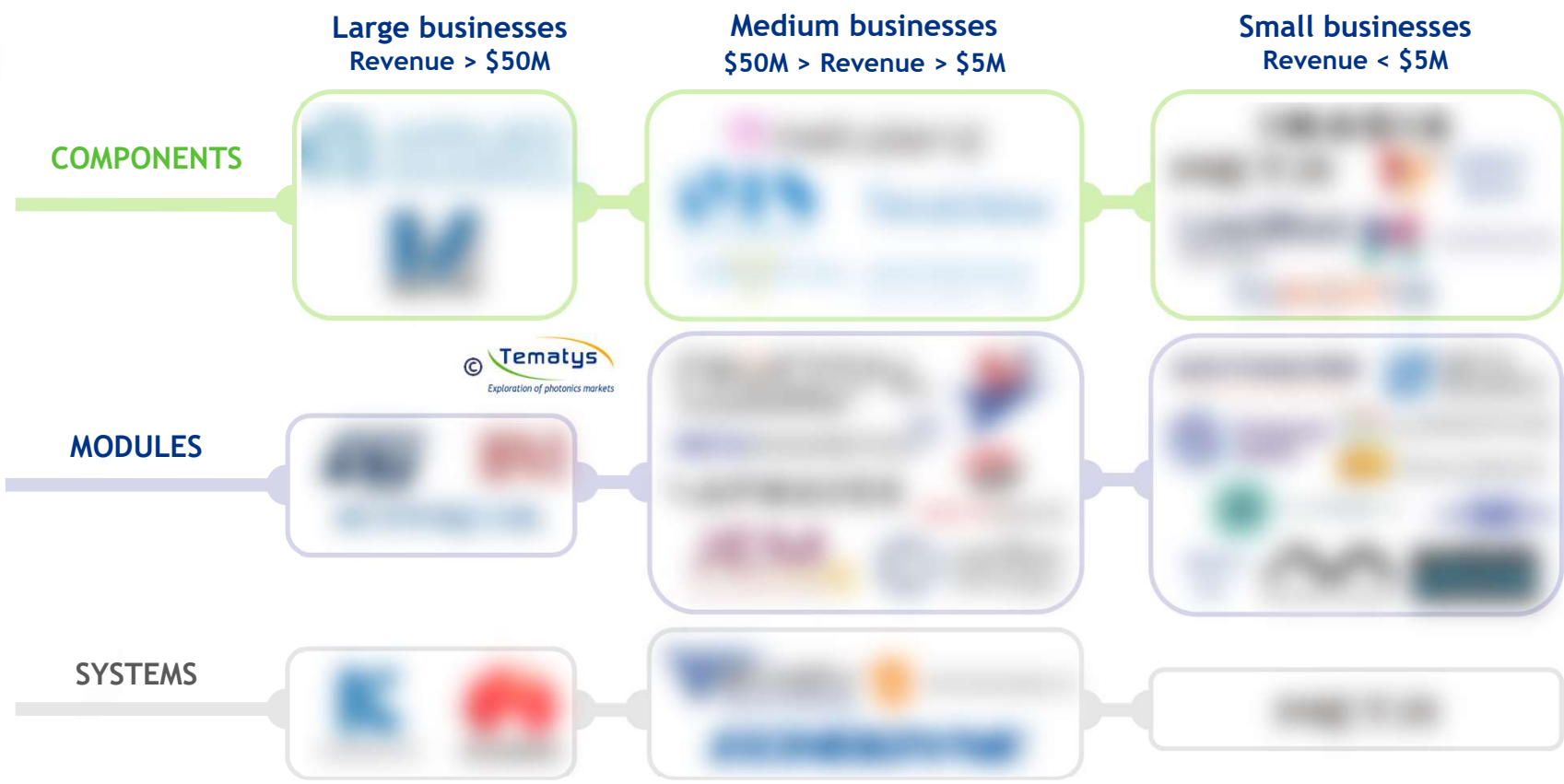
u8 Terminal, Kymeta



MESA Radar, Echodyne



Key manufacturers of Metamaterials & Metasurfaces for Optics & RF*





Metamaterials & Metasurfaces applications - Market in 2022

➤ Since this Report is focused on Optic and RF component and module markets, the **FUNCTION** of the device is taken into account when describing the applications. An in-depth analysis of the MMs and MSs functions can be found in **Chapter 4**.

SEGMENT	FUNCTION	MARKET NEEDS	END USER APPLICATION	COMPANIES	\$M 2022 MODULES
RF	Metasurface antenna	Miniaturized antenna arrays for 5G, satellite, and defense applications.	5G mobile phones, satellite communication, defense radar.	Boji, Hologram, etc.	10.0
	Metasurface lens	Flat, lightweight lenses for compact optical systems.	AR/VR headsets, compact cameras.	Boji, etc.	1.0
	Metasurface waveguide	Compact waveguide structures for integrated photonics.	Optical interconnects, compact waveguide devices.	Boji, etc.	0.5
Optic	Metasurface waveguide	Compact waveguide structures for integrated photonics.	Optical interconnects, compact waveguide devices.	Boji, etc.	10.0
	Metasurface lens	Flat, lightweight lenses for compact optical systems.	AR/VR headsets, compact cameras.	Boji, etc.	1.0
	Metasurface antenna	Miniaturized antenna arrays for 5G, satellite, and defense applications.	5G mobile phones, satellite communication, defense radar.	Boji, Hologram, etc.	10.0





Key partnerships: big players are showing up

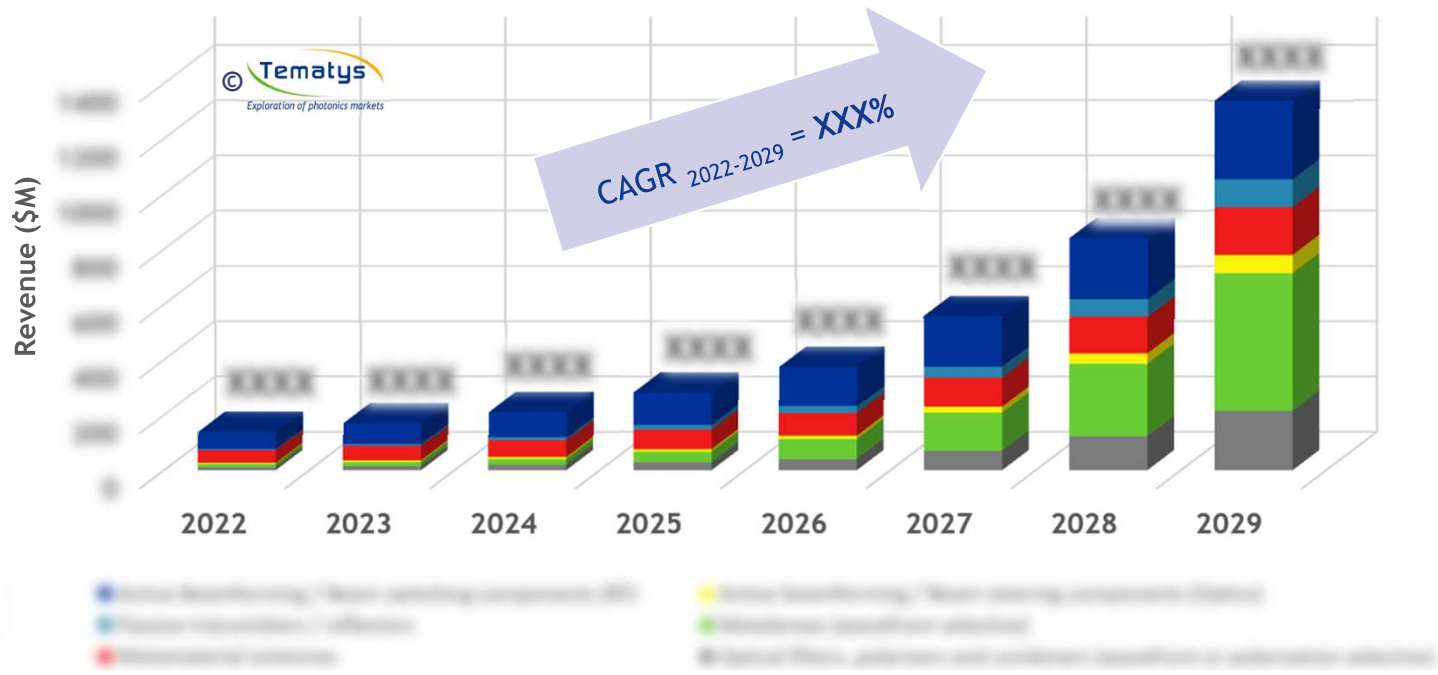
MM or MS COMPANY	STRATEGIC PARTNER	BEGINNING	AIM OF THE STRATEGIC COOPERATION

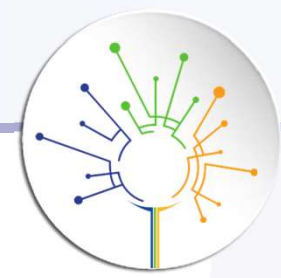




Forecast for the market of Metamaterials & Metasurfaces 2022-2029

Market of Metamaterials and Metasurfaces for Optics & RF - modules level
(including components, Optics and RF combined, 2022-2029)

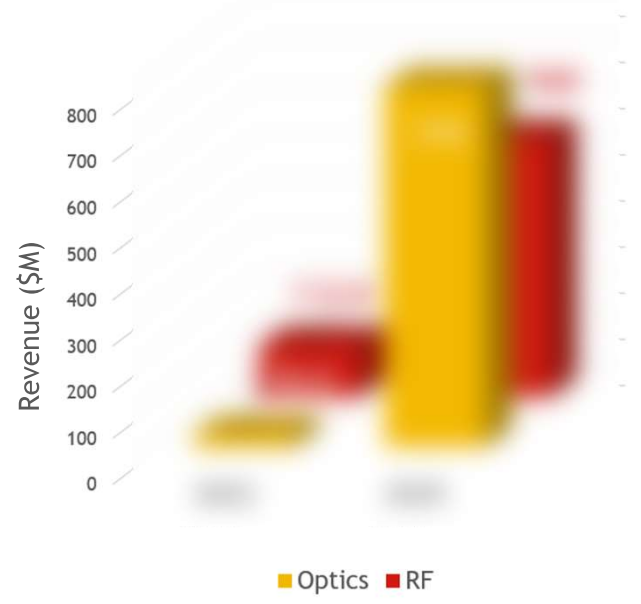




Conclusions - Optical MMs/MSs will surpass RF counterparts in 2028

- Metamaterials and Metasurfaces market will reach \$ 1329M in 2028 at the module level, with a 48.7% CAGR between 2022-2028.
- High or very high growth will be seen in all market segments, but for a metamaterial devices the CAGR 2022-2028 will exceed 40%:
 - Optical wave filters, combiners, splitters (CAGR = 54.8%),
 - Metasurfaces (CAGR = 75.9%),
 - Active optical beamformers (CAGR = 47.7%),
 - RF passive transmitters/reflexors (CAGR = 36.4%).
- Strong dominance of the RF segment over Optics in revenues (84% to 6% in 2022) will change drastically in the next years and will turn around in favor of Optics (58.2% to 41.8% in 2028).
- Driving forces of the expected growth:
 - large conversion of patents into commercial products,
 - development of new solutions thanks to large funding from investors,
 - technology maturation with strategic partnerships and funded projects.
- The relevance of Metamaterials and Metasurfaces for the Optical and RF markets, the advantages that they bring to conventional solutions as well as challenges to be overcome to reach high-volume markets are described in the next two chapters of this Report.

Forecast for the different MMs/MSs segments





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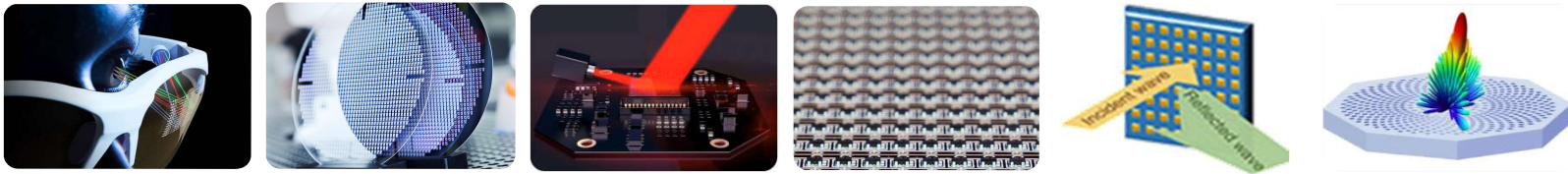
4 EMERGING PRODUCTS

- ↳ Functions
- ↳ Optics - Photonics
- ↳ RF
- ↳ Other segments (Acoustics, Mechanics)



Current functions of Metamaterials and Metasurfaces

APPLICATION SUB-SEGMENTS Tematys
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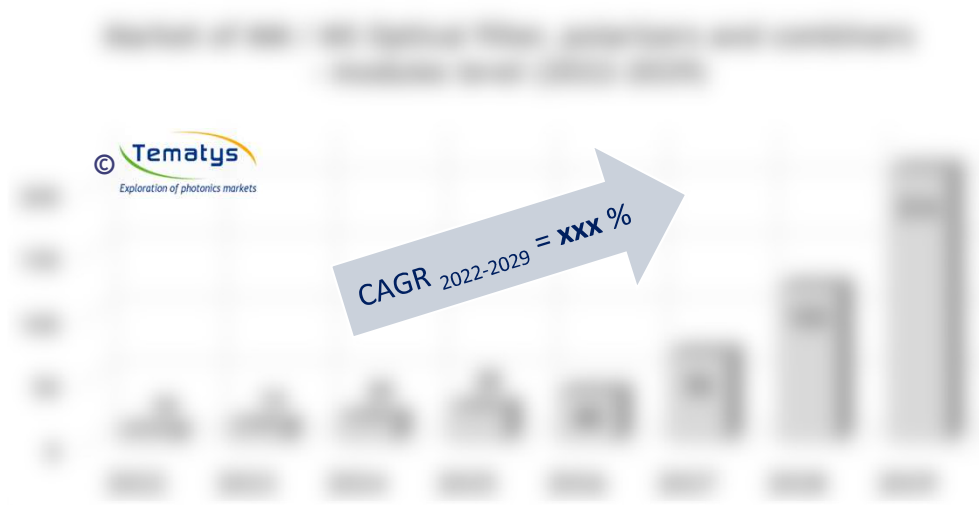


<https://www.rochester.edu/newscenter/a-new-way-to-make-ar-vr-glasses-476742/>
<https://www.linkedin.com/company/ml-technology>
<https://www.designnews.com/sensors/lumotive-beam-steering-soljd-state-lidar-eliminates-moving-parts>
<https://www.analogictips.com/metamaterials-mmwave-antennas-3d-radar-holographic-beamforming-fac/>
<https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntt202111fa2.html>



Optical filters, polarizers and combiners - description

SEGMENT	FUNCTION	MARKET NEEDS	END USER APPLICATION	MANUFACTURERS
Optics	Optical filters, polarizers and combiners	Enabling and meeting the performance of displays, sensors, cameras, smartphones, automotive, aerospace, defense, etc.	Imaging, displays, sensors, cameras, smartphones, etc.	META™ NANOHMICS edgehog



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Exploration of photonics markets

TARGETED MARKET
ALL OPTICAL COMPONENTS WITHOUT LENSES (2022) \$ xxxB

R&D ON MMs/MSs IN THIS FIELD
BRELYON™
Lochn Optics
ESSILOR
MIEUX VOIR LE MONDE
APPLIED MATERIALS®
LG
Magic Leap



Optical filters, polarizers and combiners - example of manufacturer 1/2 (META™)

INTRODUCTION

- Optical filters, polarizers or combiners serve predominantly in sensing - to increase the performance of components (detectors, lenses), to enable polarization detection in cameras, or to combine two images in AR/VR devices.
- The current use of metasurfaces in this field is, however, growing - metasurfaces serve as components that can cut out the optical radiation from glasses or goggles which pose a threat to aircraft pilots or soldiers.
- The difference between conventional filters and those exploiting metamaterials lies in the customization. Metamaterials enable the exclusion of multiple optical bands from the spectrum or help in increasing the transmittance of lenses.



Headlight™ 635nm-120mm-x-70mm (2.99€ per 10000 + film component)

PLAYER DESCRIPTION

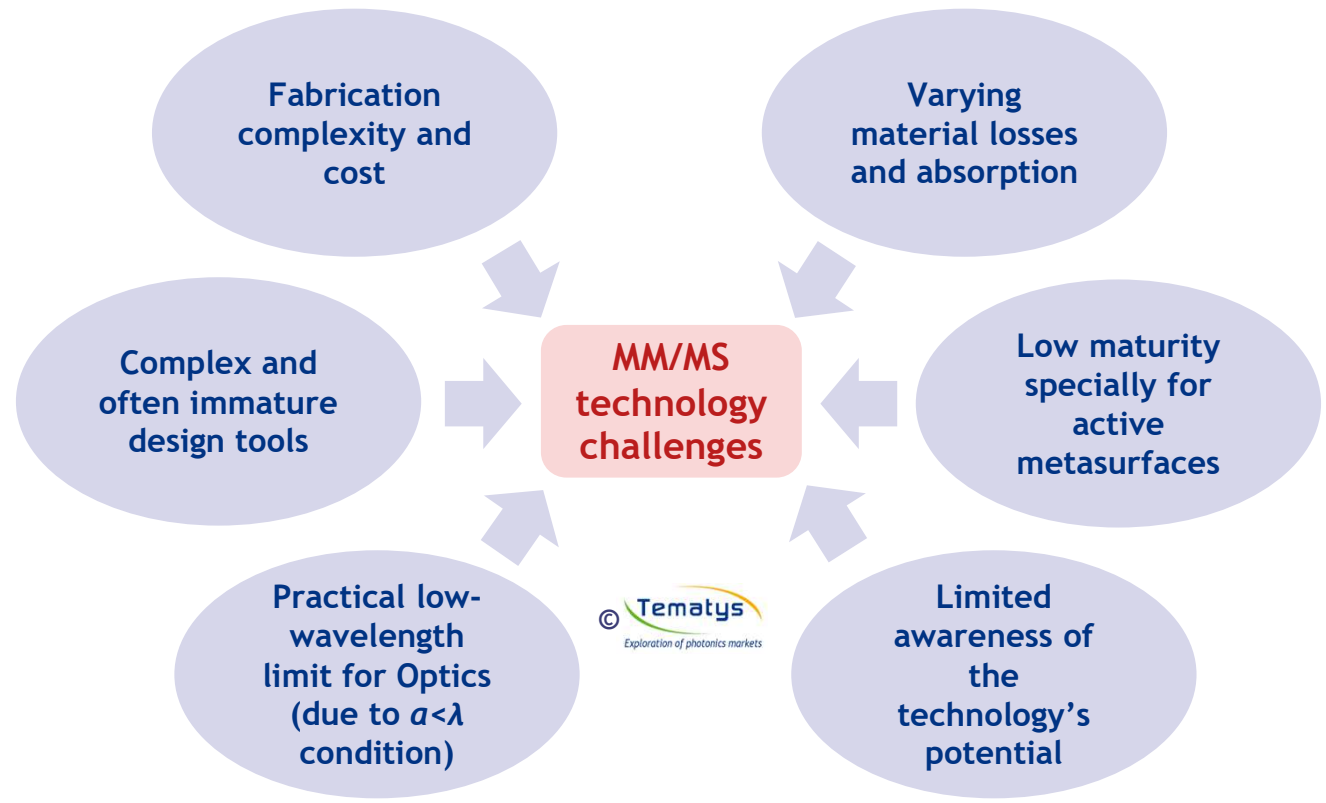
- Meta Materials Inc. is a Canadian manufacturer of metamaterial components targeting various different applications (sensing, VC, healthcare). The revenue of 5.2M in 2021 came from the sales of laser protection eyewear.
- Since 2021, prolongation of R&D led to a decrease in investment.



Laser protection eyewear (2.99€ per 100)



2023 Metamaterials & Metasurfaces Technology - Challenges





Current functions of Metamaterials and Metasurfaces - Conclusions

- There are two groups of MM and MS applications when it comes to the product development stage:
 - Applications with revenue above \$ 10M and expected CAGR 2022-2029 = 40%.
 - Applications with revenue above \$ 40M and expected CAGR 2022-2029 = 20%.
- The first group is just emerging Metamaterials, active beam components for optics, filters and polarizers, passive transmitters/reflectors. There are not many products in this range and the existing devices are not completely mature. Future growth is expected to be very high, but big players need to open the market with their killer applications in consumer products, AR/VR etc.
- The second sector bringing larger revenues is already filled with mid-size companies and the growth in this segment will not ramp up. The modules manufactured by Kyocera, Phical, Kuang-Chi (metamaterial antennas, active beam components for 5G) will need to compete with other competitors that appear successively. Big players will integrate the existing solutions into the network of 5G or 6G communication systems. These players are not likely to develop their IP since the technology is already there.

Metamaterials & Metasurfaces functions roadmap 2022-2029





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5 BIG PLAYERS SETTING TRENDS IN FUTURE APPLICATIONS

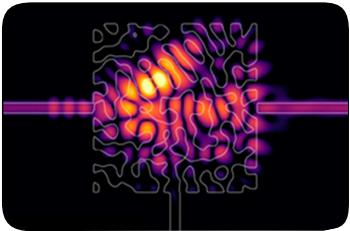
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 - Metalenses in smartphones
 - Meta-components in AR/VR devices
 - Metasurfaces for optical computing
- ↳ Potential disruption on the RF market
 - RIS for 5G/6G systems

POTENTIAL DISRUPTIONS ON OPTICAL AND RF MARKETS



Main upcoming applications and related technologies

MAIN UPCOMING APPLICATIONS OF METAMATERIALS AND METASURFACES



*RIS: Reconfigurable Intelligent Surfaces

<https://petapixel.com/2021/07/12/samsung-researching-flat-metals-tech-for-smartphone-integration/>
<https://www.magicleap.com/en-us>
<https://metamaterial.com/>
<https://www.cambridge.org/core/journals/mrs-bulletin/article/metamaterials-subwavelength-nanostructure-arrays-for-ultrathin-flat-optics-and-photonics/DD78AC35166DECCB1BD7B4C988799F78>



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