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RFID Tags for On-Metal Applications: A Brief Survey

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Abstract: Radio-frequency identification technology finds extensive use in various industrial applications, including those involving metallic surfaces. The integration of radio-frequency identification systems with metal surfaces, such as those found in the automotive sector, presents distinct challenges that can notably affect system efficacy due to metal's tendency to reflect electromagnetic waves, thus degrading the functionality of conventional radio-frequency identification tags. This highlights the importance of conducting research into academic publications and patents to grasp the current advancements and challenges in this field, aiming to improve the applications of radio-frequency identification tags technology on metal. Consequently, this research undertakes a concise review of both the literature and patents exploring radio-frequency identification technology's use for on-metal tags, utilizing resources like Google Scholar and Google Patents. The research categorized crucial aspects such as tag flexibility, operating frequency, and geographic origins of the research. Findings highlight China's prominent role in contributing to metal-focused radio-frequency identification tag research, with a considerable volume of articles and patents. In particular, flexible tags and the Ultra-High Frequency range are dominant in both scholarly and patent documents, reflecting their significance in radio-frequency identification technology applications. The research underscores a vibrant area of development within radio-frequency identification technology, with continued innovation driven by specific industrial needs. Despite the noted advances, the presence of a significant percentage of no longer valid patents suggests substantial opportunities for further research and innovation in radio-frequency identification technology for on-metal applications, especially considering the demand for flexible tags and for solutions in systems that offer specialized characteristics or are tailored for specific uses.

Keywords: rfid; radio-frequency; tags; on-metal; metal; review; survey; patents

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1. Introduction

Radio-frequency identification (RFID) technology is a rapidly growing method that uses radio-frequency (RF) signals to automatically identify objects. Its applications are vast and cover areas such as electronic toll collection, asset management, retail inventory control, animal monitoring, and vehicle protection. Internationally, each nation has its own RFID frequency designations. For example, the frequency bands for Ultra-High Frequency (UHF) RFID include 866–869 MHz in Europe, 902–928 MHz in the Americas, and 950–956 MHz in Japan and some Asian countries. RFID tags can be active, semi-passive, or passive [1].

Passive tags operate without a battery powered by the reader. They have limited range and resources, but are cost-effective and durable. Semi-passive tags have an internal battery but are also activated by the reader, similar to passive ones. Finally, the active tags are powered by batteries, enabling bidirectional communication. They offer greater range and capacity, but are, in general, larger, more expensive, and have a limited battery lifetime [2].

RFID technology is widely applied in industry, including applications on metallic surfaces. For example, within the automotive sector, RFID tags are used to monitor parts and components throughout the assembly line, enhancing inventory control and facilitating preventive maintenance. Similarly, in logistics and supply chain management, RFID tags are attached to goods stored in metal containers, ensuring accurate inventory management during the transport and storage phases.

The application of RFID technology to metallic surfaces can face various challenges that impact system performance and effectiveness. Metallic surfaces reflect electromagnetic waves, significantly impairing the performance of standard RFID tags [3]. To address this problem, the addition of at least a layer of dielectric materials between the tag and the metallic surface is necessary, which further increases the volume and costs of the tag [4,5].

A practical method to address the communication challenges faced by RFID technology on metallic surfaces involves the use of inductive coupling, which integrates the metal into the antenna component of the RFID system [6]. Inductive coupling allows energy and data to be wirelessly transferred between the RFID tag and the reader, using the metal itself as part of the antenna circuit. By incorporating the metal as part of the antenna, it is possible to overcome signal attenuation and increase communication efficiency.

Some recent studies on the use of RFID in industry can be mentioned. The article [7] reviews research on the role of RFID technology in optimizing supply chains within Industry 4.0, spanning the years from 2000 to 2021. It evaluates RFID implementation strategies to improve operational efficiency and reduce costs, using real-time data for better decision making throughout the supply chain process. The work [8] delves into optimizing the deployment of RFID technology in supply chains to increase profitability and manage uncertainties, focusing on reader spacing and quantity for various warehouse layouts. It highlights potential profit gains from strategic RFID implementation and revenue sharing. The study [9] investigates broadband/dual-band UHF RFID tag antennas for metal objects to support the use of global RFID technology, improving international trade and cost efficiency. It reviews and categorizes existing research based on design techniques for wide-band/dual-band antennas and bandwidth expansion, summarizing 38 articles. The goal is to facilitate worldwide RFID deployment through detailed analysis and design recommendations, considering operational frequencies, performance, and cost.

Reflecting on the previously discussed aspects, the need for a review that includes both academic publications and existing market patents has been identified to assess the current state of the field, thus gaining a clearer view of how metal RFID tag applications are being developed. This review will facilitate the identification of technological advancements and the development of targeted strategies for the creation of RFID labels on metallic surfaces.

The research question was defined as "How is RFID tag technology applied to solve problems in applications on metal surfaces?". The objectives of the research are to extract the following information from the articles and patents:

- What problem was solved by the publication or patent?
- In what country was the research carried out or the patent published?
- What was the RFID operating frequency used in the application?
- What was the flexibility of the tag used in the application?

The organization of this work follows the following structure. Section 2 provides a brief explanation of the survey methodology to select articles and patents in this work. Section 3 presents the review results and analyzes some of the findings, including the issue addressed by the publication, the country where the research was conducted, the frequency addressed in the article, whether the label is flexible or hard, and whether the patent remains valid, among other information. Section 4 presents the discussions, and finally, in Section 5, the conclusions of this article are presented.

2. Materials and Methods

This survey aims to comprehend the application of RFID tags technology on metal surfaces by analyzing scientific articles and patents. Articles were gathered from Google Scholar, covering various databases, while patents were searched on Google Patents and Lens platforms. The study reviewed articles published from 2006 to 2023 and patents from 2002 to 2023, focusing solely on publications in journals and conference proceedings to ensure quality. Keyword combinations such as "RFID", "radio-frequency", "on-metal", "metal", "metallic", "anti-metal", "off-metal", and "tag" were utilized for the search. The selection criteria for both articles and patents are detailed in Table 1.

Table 1. Criteria used for inclusion and exclusion of both articles and patents.

Criteria	Type
The document is not related to an application of a RFID tag in a metallic surface	Exclusion
The document is duplicated	Exclusion
The document is not in the selected year range (2006–2023 for articles and 2002–2023 for patents).	Exclusion
The document is not available online	Exclusion
The document is related to an application of a RFID tag on a metallic surface	Inclusion

Table A1 presents a list of all selected articles, and Figure 1a illustrates the distribution regarding the type of publication, whether it was in a journal or conference/congress. Figure 1b shows the distribution of the selected patents according to the search engine used.

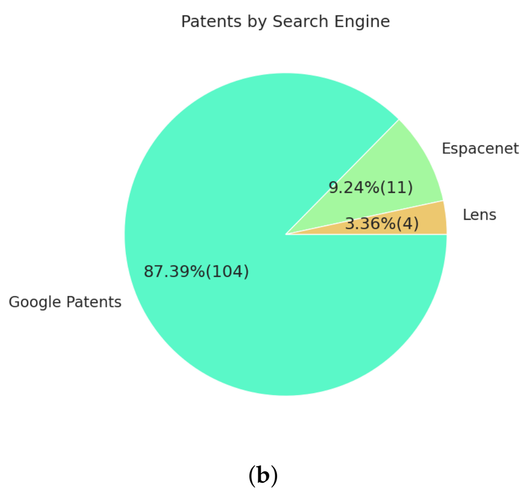


Figure 1. Distributions of the selected articles and patents. (**a**) Selected articles by publication type. (**b**) Selected patents by search engine.

This study aimed to extract relevant information from articles and patents to support the current landscape of academic research and the market in this field of application. Regarding articles, this study sought the year of publication, the country where the research was conducted, the frequency used by the tag, whether the tag was flexible or hard, and the publication category according to the type of problem it aims to address. Regarding patents, the current validity status of the patent was sought, along with its year of publication, the country of publication, the type of frequency of the tag, whether it is flexible or hard, and its category, as was investigated for scientific articles. This work used ChatGPT v4.0 [10] as a text translation tool.

3. Results

This section is divided between the results obtained from the research on articles and patents for better understanding.

3.1. Articles

Figure 2 displays the number of selected articles according to their year of publication. It is evident that there has been an increase in the number of publications in recent years, particularly in 2020, 2022 where the peak occurred, and 2023.

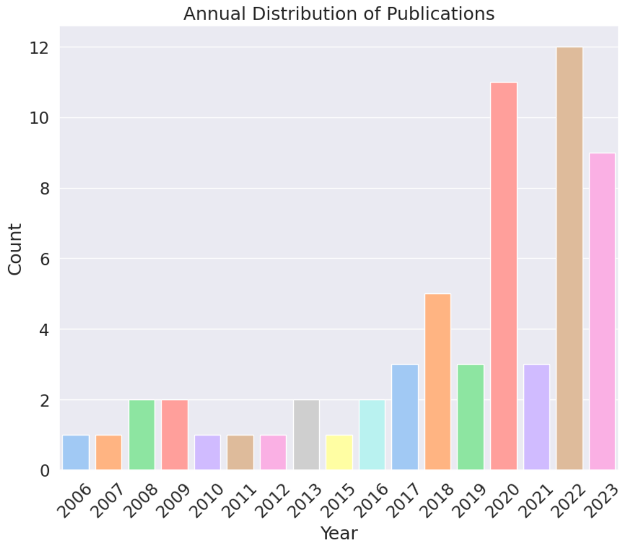


Figure 2. Distribution of the publications by year.

A compilation of countries was made, as referenced in the publications, to identify the locations of the experiments. When the publication did not specify the location of the experiment or if no experiment was performed, the countries of the authors were used for this purpose. Figure 3 illustrates that China, which leads with 27 publications and Malaysia, which follows with 14 publications, are the countries with the highest number of research papers published in this field.

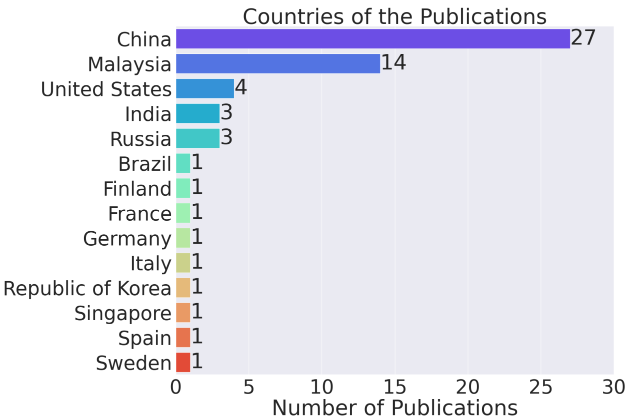
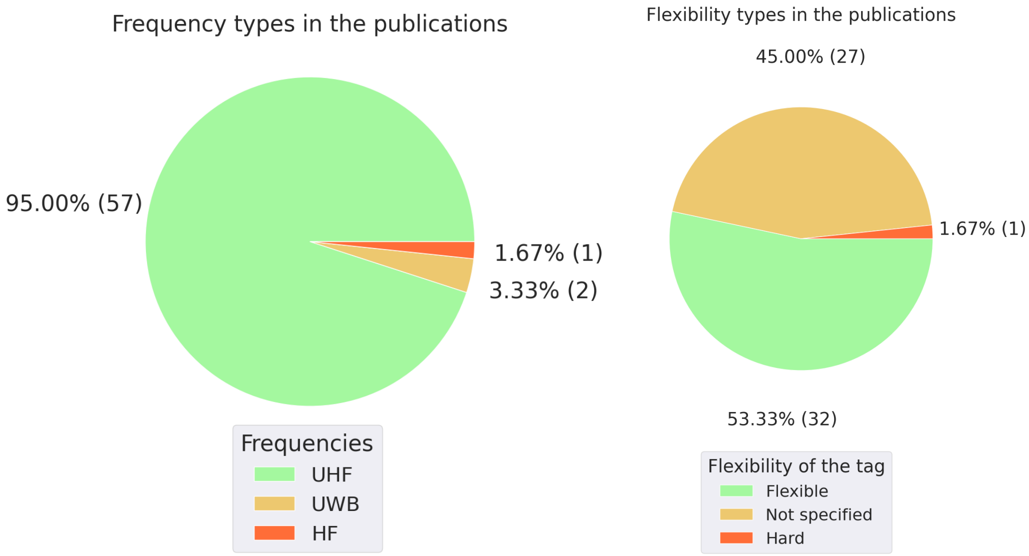


Figure 3. Distribution of the articles by country.

Figure 4a shows that the frequency type most commonly used in the experiments was UHF (Ultra-High Frequency), which represented nearly all, with 57 articles. UWB (Ultra-Wide Band) and HF (High Frequency) were also mentioned.

Figure 4b reveals that nearly half of the articles did not specify whether the tag being used or developed was flexible or hard. Only one mentioned that the tag was hard, while the majority, with 32 publications, indicated that the tag was flexible.



(**a**) (**b**)

Figure 4. Distributions of the frequencies and the flexibility types used in the publications. (**a**) Frequencies used in the articles. (**b**) Flexibility types used in the articles.

For a more detailed categorization of the articles, they have been sorted into ten distinct categories. In the cases where an article pertains to multiple categories, a primary category has been assigned for classification purposes. Figure 5 shows the count of articles for each category, and Table A2 details the categorization of each article. The categories are delineated as follows:

- On-Metal RFID Tag Design and Performance: This category encompasses research focused on the development and optimization of RFID tags specifically designed to function effectively on metal surfaces. These studies address unique challenges posed by metal environments, such as signal reflection and interference, proposing solutions to maintain high performance in terms of read range, data accuracy, and durability of RFID tags when attached to metallic objects.
- Antenna Design and Optimization: Articles classified under this category explore the intricacies of RFID antenna design, including the development of novel antenna structures, the optimization of existing designs for better performance, and the application of advanced optimization techniques. The focus is on enhancing the efficiency, read range, and adaptability of RFID antennas to various operational conditions and frequencies.
- RFID Tag Performance Enhancement Techniques: This category captures studies that propose methods and technologies to improve the overall performance of RFID tags. This includes enhancing the read range, sensitivity, and reliability of tags through material innovation, electromagnetic band-gap materials, and other performance enhancing techniques, especially in challenging environments.
- Multi-Band and Wideband RFID Applications: Research articles in this category explore the development and application of RFID systems that operate across multiple frequency bands or utilize wideband technology. These studies aim to improve the versatility and adaptability of RFID systems, enabling them to cater to a wider range of applications and standards in different regions.
- RFID Applications for Safety and Health Monitoring: This category includes studies that apply RFID technology to monitor safety and health, such as tracking worker locations in hazardous environments, monitoring structural health, and detecting changes in environmental conditions. The focus is on leveraging RFID for real-time data collection and analysis to enhance safety and preventive measures.

- Innovative Materials and Structures for RFID Tags: The articles in this category focus on the exploration and application of innovative materials and structural designs in the creation of RFID tags. This includes the use of high-conductivity graphene, flexible substrates, and novel antenna structures to improve tag performance and enable new applications, particularly in challenging or unconventional environments.
- RFID System Analysis and Environmental Performance Evaluation: This category covers comprehensive studies on the analysis of RFID systems' performance in various environmental conditions. It includes the evaluation of factors that affect system efficiency, such as interference, materials, and operational scenarios, to understand and mitigate potential performance problems.
- Energy Harvesting and Autonomous RFID Systems: Research in this category is dedicated to the development of RFID systems that can harvest energy from their surroundings to power themselves. This includes innovations in energy harvesting techniques and the design of autonomous RFID sensors and tags for applications where battery replacement is impractical.
- RFID for Material Identification and Sensing: Articles classified here discuss the use of RFID technology for identifying materials and sensing environmental or structural changes. This includes methods for passive material identification, crack sensing, and integrating RFID with sensor technology to expand its application beyond traditional tracking and identification.
- Advanced Computational Techniques for RFID Design: This category highlights studies employing advanced computational methods, such as deep learning and particle swarm optimization, in the design and optimization of RFID systems. The focus is on using these techniques to predict electromagnetic responses, optimize antenna designs, and improve the overall performance and efficiency of RFID tags and systems.

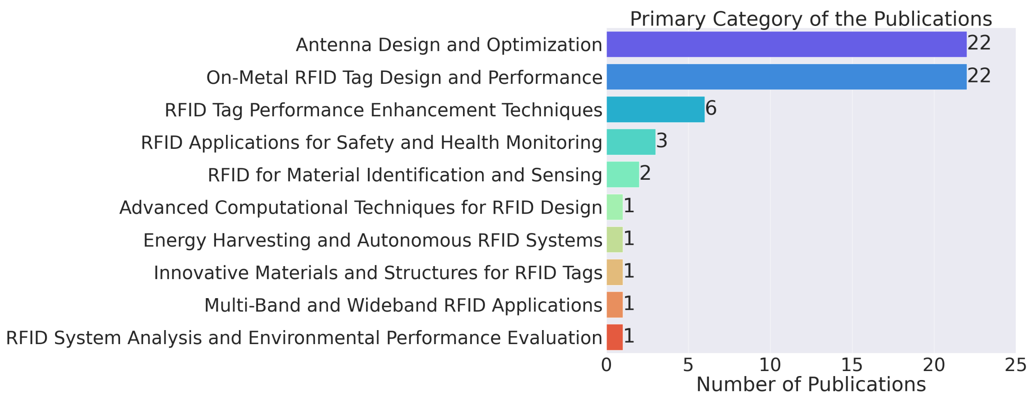


Figure 5. Distribution of the primary categories of the publications.

3.2. Patents

Figure 6 indicates that the majority of the selected patents were in active status, which means that they were valid at the time the research was conducted. Patents that were pending or expired were considered to have an invalid status.

Figure 7, which presents the number of patents by year of publication, shows a growing market interest in this area in recent years, especially after a peak in 2017, when 18 patents were registered.

Figure 8 reveals that a higher number of selected patents were registered in China, totaling 57, and in the United States, with a total of 40. Patents that were registered through the PCT-International Patent System [11] were classified as "International".

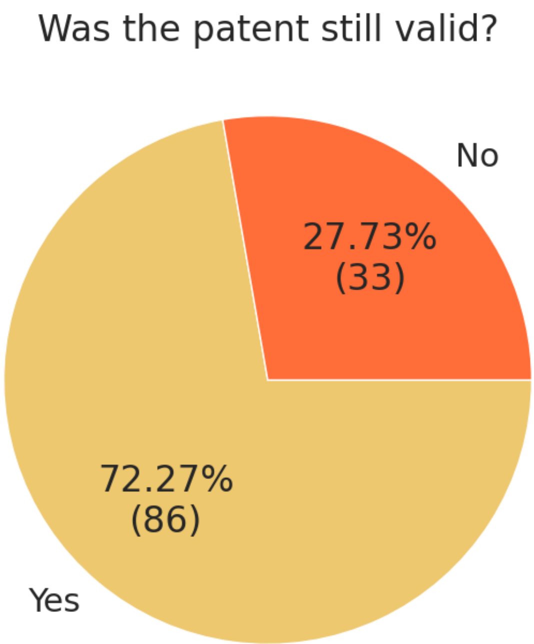


Figure 6. Amount of valid and invalid patents.

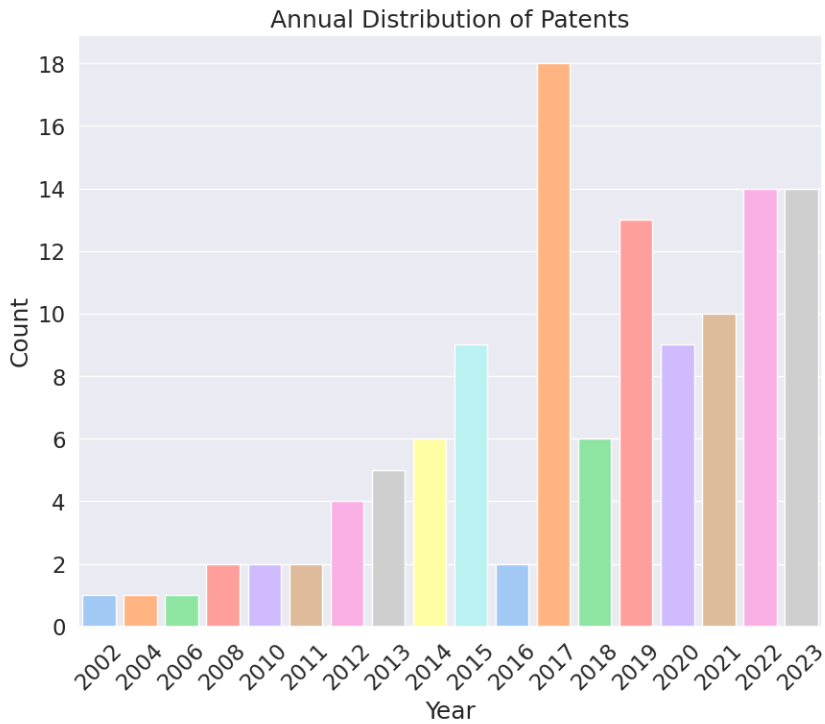


Figure 7. Distribution of the patents by year of publication.

Figure 9a shows the frequency ranges identified in the patents. The "Generic RFID" category, which constituted the majority, encompasses patents designed for a flexible approach towards frequency usage. Such patents are applicable across a broad spectrum of frequency ranges, making them adaptable for a wide array of applications and sectors. This versatility promotes ease of integration and flexibility of use. Among those who specified their operating frequency range, UHF was predominant. HF and 2.4 GHz frequencies were also mentioned. One of the publications discussed employing both HF and UHF technologies, leading to its classification under both categories in the figure.

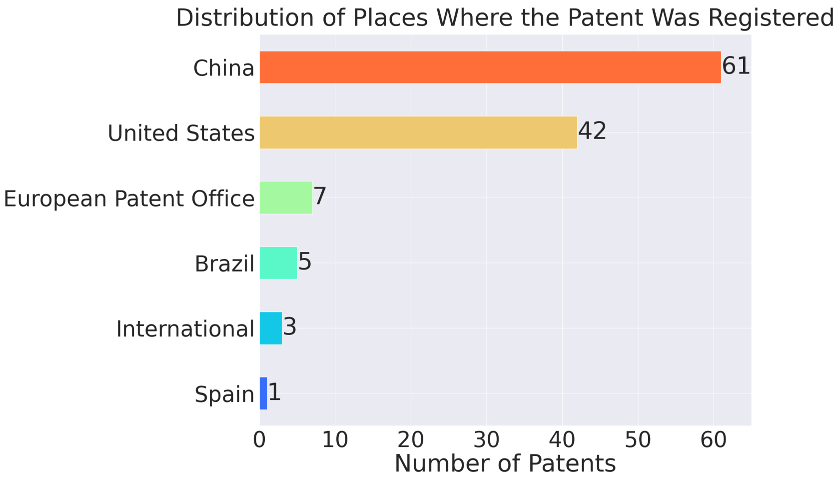


Figure 8. Distribution of the patents by country.

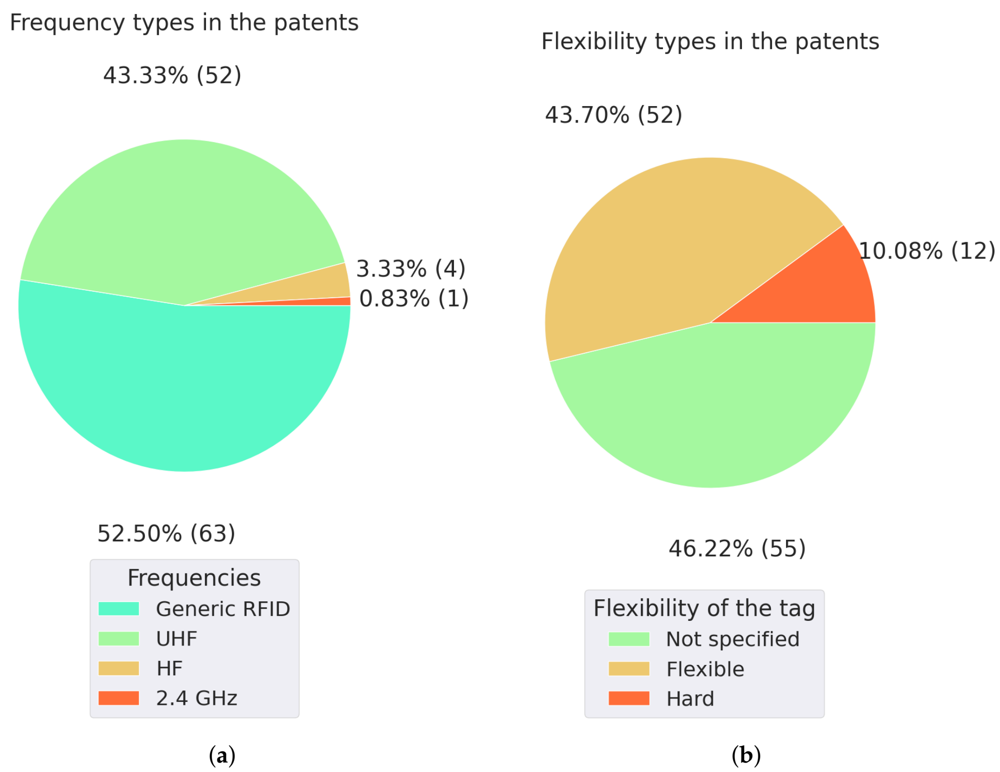


Figure 9. Distributions of the frequencies and the flexibility types used in the patents. (**a**) Frequencies used in the patents. (**b**) Flexibility types used in the patents.

Figure 9b indicates that most of the patents did not specify whether the tag was flexible or rigid. Among those who provided this information, the vast majority were identified as flexible, accounting for 52 patents.

To achieve a more granular categorization of the patents, they have been systematically arranged into ten distinct categories. When a patent is applicable to multiple categories, a primary category has been selected for classification purposes. These categories are designed to encapsulate the broad spectrum of innovations and applications within the realm of RFID technology use on tags for metal, facilitating a comprehensive and organized review. Figure 10 shows the number of patents for each category. The categories were defined as follows:

1. RFID Tag Design for Metal Surfaces: Focuses on innovations to overcome challenges associated with RFID tagging on metal surfaces. Includes tags optimized for metal, anti-metal RFID tags, and designs utilizing ferromagnetic flakes or metal fasteners as antennas.
2. RFID in Healthcare and Medical Instrument Tracking: Covers RFID applications to track medical instruments, produce surgical trays, and identify medical vials. Includes encapsulated devices in surgical instruments and RFID memory tags with metal components.
3. Advanced RFID Tag Structures and Materials: Include items detailing structural innovations in RFID tags, such as 3D structures, dual-resonance tags, and tags with composite layers for improved performance and environmental resistance.
4. RFID Systems for Authentication and Security: The focus is on the use of RFID to authenticate precious metals, jewelry, and other valuable items. Includes tamper-proof and tamper-resistant designs, anti-dismounting structures, and tags with integrated security features.
5. Smart RFID Tag Assemblies and Integration: Covers smart tag assemblies that integrate RFID technology with microchips and antennas, including designs for embedded systems, encapsulated electronic devices, and integrated circuits for tracking and data transmission.
6. RFID Applications in Industrial Settings and Logistics: Includes RFID solutions for inventory management, asset tracking, and enhancing operational efficiency in industrial settings. Covers tags for railcar wheelsets, gas turbine engines, and automated spray painting lines.
7. RFID for Environmental and Material Adaptation: Focuses on RFID tags designed to function in challenging environments or on difficult substrates. Includes heat-resistant tags, flexible tags for uneven surfaces, and designs optimized for liquid monitoring.
8. Innovative RFID Interfaces and Systems: Encompasses novel RFID-based interfaces and systems, such as mixed reality interfaces for Computer Numerical Control (CNC) production, RFID for retail attention, and intelligent inventory systems with RFID electronic labels.
9. RFID Tag Manufacturing and Assembly Techniques: Details methods and processes for producing and assembling RFID tags and components, including sequential introduction of structural modules, "flip chip" assembly on fabric substrates, and production of microstrip patch antennas.
10. Specialized RFID Features and Applications: Covers RFID tags and systems with specialized features or for specific applications, such as temperature sensing, liquid monitoring, flexible anti-metal labels, and RFID tags with light-emitting capabilities.

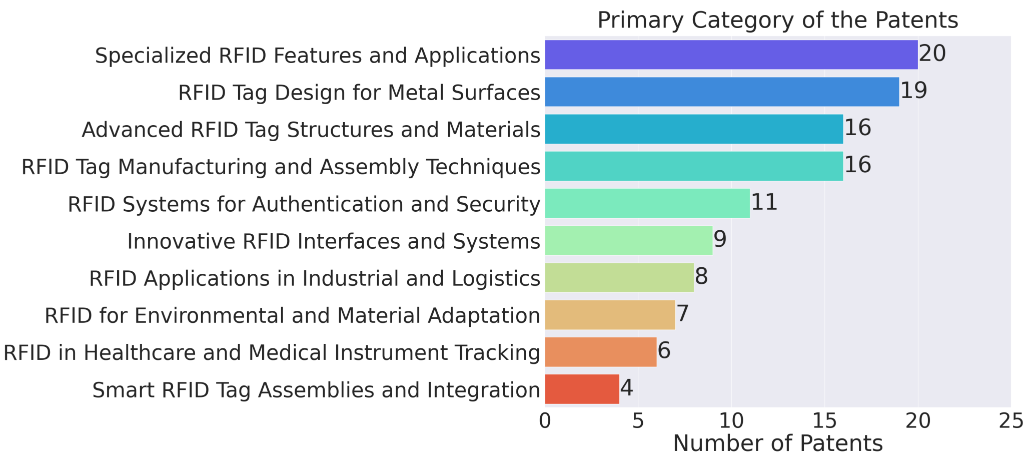


Figure 10. Distribution of the primary categories of the patents.

4. Discussion

Regarding Figure 2, there was a marked increase in publications in 2020, followed by a decrease in 2021, likely due to the impact of the COVID-19 pandemic. However, the publications rebounded in 2022 and 2023. Based on this pattern, we can anticipate a continued upward trend in the publication volume within this domain, underscoring the enduring interest and relevance of this topic in both academic and industry circles.

Figure 4a shows that almost all articles chose to use the UHF range. This frequency offers better performance in environments with high levels of interference from liquids and metals, which traditionally impede RFID signals. This capability makes UHF tags more versatile and reliable for a wide range of applications. They also offer a better reading range and a higher data transfer rate compared to lower frequencies. Observing these data in the patents in Figure 9a, it is observed that this preference is also repeated, even though most patents do not specify the frequency that will be used to offer greater adaptability to the application.

Additionally, a substantial share of the studies analyzed use flexible tags, representing approximately 53.33% of the total, as shown in Figure 4b. These tags are preferred in various applications because of their ability to conform to various surfaces and conditions. They find particular utility in industries such as logistics, smart packaging, healthcare, and retail due to their versatility. In contrast, only 1.67% of the articles explored the application of hard tags. Hard tags are typically used in scenarios that require high durability and resistance to harsh environments, including industrial and transportation settings. The predominant focus on flexible tags in academic research highlights the significant endeavor to develop tags that are functional, durable, and adaptable to metal surfaces simultaneously. This trend is mirrored in the market, as indicated in Figure 9b, which shows that among patents that discuss the flexibility of tags, the majority describe them as flexible.

Finally, the publications were categorized, and two of them stood out: "Antenna Design and Optimization" and "On-metal RFID Tag Design and Performance". In the category "Antenna Design and Optimization", significant interest is probably related to the critical importance of antennas in the effectiveness and performance of RFID systems. Researchers are dedicating their efforts to developing new techniques for antenna design and optimization, with the aim of improving the efficiency, range, and reliability of RFID communications in metal applications. In contrast, in the "On-Metal RFID Tag Design and Performance" category, the increase in the adoption of RFID tags in industrial environments, where metal is abundant, may be the main driver of this interest. Developing RFID tags that work effectively and reliably when applied directly to metal surfaces presents unique challenges due to electromagnetic interference caused by the metal.

Lastly, similar to the categorization process for articles, patents were also organized into categories, with "Specialized RFID Features and Applications" emerging as a prominent category. This category, which comprises 20 patents, highlights the increasing market need for highly specialized and customized RFID solutions for specific applications involving on-metal tags. It includes a diverse array of innovations, covering advanced RFID tag features like temperature sensing and liquid monitoring, as well as developments in anti-metal flexible tags and RFID tags capable of emitting light.

5. Research Gaps and Future Extensions

This section will outline various research gaps and opportunities for future extensions that arise, in order to enhance the understanding of the use of RFID technology on metal surfaces and assisting researchers in driving innovation.

- Future expansions of this study could include using a broader array of databases to explore articles and patents, aiming to cover as many relevant publications as possible. Expanding the temporal range further back could also provide insights into the evolution of RFID technology.
- Further investigation could also consider aspects like the cost of tag production and its performance, which were not covered in this work. An economic analysis could

provide valuable insights into the cost-effectiveness and ROI of implementing RFID systems on metallic surfaces across different industries.

- Search for studies that use other technologies in conjunction with RFID tags on metal surfaces, such as integrations with the Internet of Things (IoT) and machine learning systems, and verify their advantages and limitations when compared to traditional use in this context.
- A comparative study between the use of RFID tags and other tracking technologies, such as Bluetooth, on a metal surface could provide some insights into the advantages and limitations of each.
- An important aspect that could be explored in the future is how extreme usage conditions, such as high temperatures, which are commonly associated with the use of RFID tags on metal, affect the reliability and durability of these tags.
- Future studies could also focus on materials science and how they impact the performance of RFID tags on metal surfaces, covering the latest advancements in this field.

6. Conclusions

This research involved a comprehensive review of the literature and a patent search to explore the application of RFID technology in on-metal tags. A noticeable uptick in both articles and patents related to this topic was observed in recent years. The primary goals of this study were to classify key issues such as tag flexibility, operating frequency, country of patent registration, and location of the research, among other vital details. This was studied to gain a deeper understanding of the research landscape and market dynamics surrounding on-metal tags.

The findings of this study indicate that China is a leading contributor to research on metal-focused tags, boasting substantial counts in both articles and patents. Additionally, two notable trends were observed: flexible tags dominate the counts in both articles and patents, and the UHF frequency range is prominently featured, showcasing its prevalence in both the literature and patent filings.

The categorization of the publications revealed two main areas of interest: antenna design and optimization, and performance of on-metal RFID tags. The focus on antenna design highlights the industry's effort towards enhancing RFID system effectiveness, especially in overcoming challenges associated with metal environments. This includes advancements in antenna technology to improve communication efficiency, range, and dependability. Simultaneously, the interest in on-metal RFID tag design underscores the growing implementation of RFID technology in metal-rich industrial settings, addressing the challenges of electromagnetic interference unique to these applications. Moreover, the organization of patents into categories identified "Specialized RFID Features and Applications" as a significant area, reflecting the market demand for tailored RFID solutions for on-metal applications. This category encompasses innovations ranging from advanced tag functionalities, such as temperature detection and liquid monitoring, to the development of anti-metal flexible tags and light-emitting RFID tags, indicating a broad scope of research and development aimed at meeting specific market needs.

Finally, it is important to emphasize that there is still ample room for research and patents in this field, considering that 27.33% of the patents found during the investigated period are no longer valid. This indicates that there is a significant opportunity for new developments and innovations in this area, especially considering the demand for flexible tags, which can contribute to further advances in RFID technology applied to on-metal tags. There is also significant demand for solutions in systems that offer specialized characteristics or are tailored for specific uses, such as flexible anti-metal labels or light-emitting anti-metal tags.

Future expansions of this work could involve utilizing a wider range of databases to investigate articles and patents to encompass as many relevant publications as possible. Additional aspects such as the cost of tag production and its performance could be examined, which were beyond the scope of this current review.

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Abbreviations

The following abbreviations are used in this manuscript:

RFID	Radio-frequency identification
RF	Radio-frequency
UHF	Ultra-High Frequency
HF	High Frequency
UWB	Ultra-Wide Band

Appendix A

Table A1. List of the selected articles for the survey.

Reference	Title	Year	Publisher
[12]	Miniature Long-Range Ceramic On-Metal RFID Tag	2022	IEEE
[13]	A Novel Antenna Design for Passive RFID Transponders on Metal Surfaces	2006	IEEE
[14]	Small Wideband Antenna for On-Metal UHF RFID Tag Design	2021	IEEE
[15]	Characteristics of passive UHF RFID tags on metal slabs	2009	IEEE
[16]	UHF RFID Tags for On-/Off-Metal Applications Fabricated Using Additive Manufacturing	2017	IEEE
[17]	Coupled-PILAs for Miniature On-metal RFID Tag Design	2020	IEEE
[18]	RFID tag antenna for use on metal	2010	IEEE
[19]	Low-profile, high-permeability antennaless RFID tags for use on metal objects	2012	IEEE
[20]	Compact ceramic on-metal RFID tag	2022	IEEE
[21]	M-Shaped Folded-patch Antenna for On-Metal UHF RFID Tag Design	2022	IEEE
[22]	Loop-Coupled Small Antenna With Enhanced Bandwidth for On-Metal UHF RFID Tag Design	2023	IEEE
[23]	Flexible Low-Profile On-Metal Tag Antenna for Asset Tracking and Identification	2022	IEEE

Table A1. *Cont.*

Reference	Title	Year	Publisher
[24]	Complementarily Coupled C-Shaped Microstrip Patches With Wide-Range Frequency Tuning Capability for Metal-Applicable UHF RFID Tag Design	2022	IEEE
[25]	UHF RFID Tag Design Using Theory of Characteristics Modes for Platform-Tolerant and Harsh Metallic Environments	2022	IEEE
[26]	Bio-Inspired Circular-Polarized UHF RFID Tag Design Using Characteristic Mode Analysis	2023	IEEE
[27]	Circularly Polarized RFID Tag Antenna Design for Metallic Poles Using Characteristic Mode Analysis	2019	IEEE
[28]	A Compact UHF-RFID Tag Antenna Based on PIFA Structure for Two-Side Anti-Metal Application	2023	IEEE
[29]	Investigation of Low-Profile RFID Antenna Using AMC Substrate for Anti-Metallic Application	2018	IEEE
[30]	Low Cost Passive UHF RFID Packaging with Electromagnetic Band Gap (EBG) Substrate for Metal Objects	2007	IEEE
[31]	Passive UHF RFID with ferrite electromagnetic band gap (EBG) material for metal objects tracking	2008	IEEE
[32]	Passive UHF RFID Packaging With Electromagnetic Band Gap (EBG) Material for Metallic Objects Tracking	2011	IEEE
[33]	Multi-system, multi-band RFID antenna: Bridging the gap between HF- and UHF-based RFID applications	2008	IEEE
[34]	Flexible Folded-Patch Antenna with Tapered Edges for Metal-Mountable UHF RFID Tag Design	2020	IEEE
[35]	Metal-mountable microstrip RFID tag antenna for high impedance microchip	2009	IEEE
[36]	A new UHF anti-metal RFID tag antenna design with open-circuited stub feed	2013	IEEE
[5]	Design of UHF RFID broadband anti-metal tag antenna applied on surface of metallic objects	2013	IEEE
[37]	A Compact UHF RFID Tag Antenna for Anti-Metal Used on Both Sides	2020	IEEE
[38]	Compact long-range ceramic RFID tag for on-metal and non-metal applications	2022	IEEE
[39]	Research on Response Characteristics of Antenna Sensor for Metal Structure Defect Detection	2020	IEEE
[40]	Bendable Folded-Patch Antenna With Resonant Ring Manufactured Based on Foam Support and PET Substrate for On-Metal UHF RFID	2023	IEEE
[41]	A Novel Multiresonant Chipless RFID Tag for Directional Strain Measurement on Metal Surface	2023	IEEE

Table A1. *Cont.*

Reference	Title	Year	Publisher
[42]	High-Efficient Compact Folded-Patch Antenna Fed by T-Shaped L-Probe for On-Metal UHF RFID Tag Design	2020	IEEE
[43]	A small flexible anti-metal RFID tag antenna	2016	IEEE
[44]	A Miniaturized Tag Antenna for UHF RFID Metallic Objects	2023	IEEE
[45]	Small UHF RFID tag antenna for metallic objects	2015	IEEE
[46]	Microstrip Dipole UHF-RFID Tag Antenna for Metal Object Tagging	2016	IEEE
[47]	A UHF RFID Tag Embeddable in Small Metal Cavities	2018	IEEE
[48]	Detection of Strain Magnitude and Direction Based on an RFID Sensor Array	2022	IEEE
[49]	Compact Magnetic Loop Antenna for Omnidirectional On-Metal UHF Tag Design	2020	IEEE
[50]	Slotted Folded Patch Antenna With Double-T-slots for Platform-Insensitive UHF Tag Design	2019	IEEE
[51]	Miniaturized Dipolar Patch Antenna With Narrow Meandered Slotline for UHF Tag	2017	IEEE
[52]	Folded Patch Antenna With Tunable Inductive Slots and Stubs for UHF Tag Design	2018	IEEE
[53]	Compact Orientation Insensitive Dipolar Patch for Metal-Mountable UHF RFID Tag Design	2018	IEEE
[54]	Compact Folded Dipole With Embedded Matching Loop for Universal Tag Applications	2017	IEEE
[55]	Platform Tolerant RFID Tag Antenna Design for Safety and Real-Time Tracking of On-site Workers at Riskier Workplaces	2023	Hindawi
[56]	Flexible Anti-Metal RFID Tag Antenna Based on High-Conductivity Graphene Assembly Film	2021	MDPI
[57]	Analysis of Electromagnetic Interference for Anti-Medal UHF RFID Temperature Tag in High Power Electronic Equipment	2023	MDPI
[58]	Frequency Switchable Global RFID Tag Antennae with Metal Compatibility for Worldwide Vehicle Transportation	2023	MDPI
[59]	Machine Learning-Based Structural Health Monitoring Using RFID for Harsh Environmental Conditions	2022	MDPI
[60]	Design of a new anti-metal RFID temperature tag antenna based on short-circuit stub structure	2022	Science Direct
[61]	Ultra slim and small UHF RFID tag design for mounting on curved surfaces	2021	Science Direct
[62]	Stretchable chipless RFID multi-strain sensors using direct printing of aerosolized nanocomposite	2020	Science Direct

Table A1. *Cont.*

Reference	Title	Year	Publisher
[63]	Research on Performance of Anti-metal RFID in Field Test of Type and 500 kV Substation	2020	IOP Science
[64]	Development of RFID Tag Antenna With Graphene Material Using Deep Learning	2022	IOP Science
[65]	Design of UHF Tag Antenna Based on Internet of Things	2020	IOP Science
[66]	A Compact Folded RFID Tag Antenna with Nested Deformable Rings for Two-Side Anti-Metal Application	2022	Progress In Electromagnetics Research (PIER)
[67]	A Novel Ultra High Frequency Flexible Anti-Metal Tag Antenna Design	2019	World Scientific Research Journal (WSRJ)
[68]	Wireless and autonomous sensor for Integrated Engine Health Management	2018	PHM Society European Conference
[69]	Surface crack detection and monitoring in metal structure using RFID tag	2020	Emerald
[70]	Design of an UHF RFID Anti-metal Tag Antenna	2020	International Core Journal of Engineering

Table A2. Categorization of the selected articles.

Category	References
On-Metal RFID Tag Design and Performance	[5,12,14,17,19,21,23,28,35,37,38,40,42–44,51–54,66,67,70]
Antenna Design and Optimization	[13,18,20,22,24–27,29,33,34,36,41,45–47,49,50,56,60,61,65]
RFID Tag Performance Enhancement Techniques	[15,16,30–32,57]
Multi-Band and Wideband RFID Applications	[58]
RFID Applications for Safety and Health Monitoring	[39,55,69]
Innovative Materials and Structures for RFID Tags	[62]
RFID System Analysis and Environmental Performance Evaluation	[63]
Energy Harvesting and Autonomous RFID Systems	[68]
RFID for Material Identification and Sensing	[48,59]
Advanced Computational Techniques for RFID Design	[64]

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