The Progress of the Latin American Photonics Community - and a Brief Mention about Mechanical Nanoresonators

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***Abstract*—In this article, we will briefly review the history and progress of photonics in Latin America, describing the discipline's development over the years and its collaborations with the rest of the world's countries. Among the ten countries analyzed, we will focus mainly on the most developed players in the field, taking the three most significant in terms of scientific weight: Brazil, Mexico, and Argentina, and the very interesting, more recent developments acquired by Chile, Colombia, and Ecuador. On the other hand, we will also shortly review the activities we have developed in Argentina in nanophotonics, specifically in mechanical nanoresonators.**

***Index Terms*—Latin America, photonics, nanophotonics, nanoresonators.**

I. Introduction

THE vast territory of Latin America, from Mexico to Argentina, has a rich pre-Columbus history with well-developed cultures as well as the better-known post-European-conquest history. The earliest traces of the ancient history of optics date back to the time of the Olmec Indians, and their stone curved mirrors dated as early as 1000 BCE to a few centuries BCE, which, according to archaeological experts, were used for making fire, self-contemplation, and ornamentation, medicine, divination, astronomy, and offerings to the sun god [1].

During the colonial period, the Jesuit priest Buenaventura Suarez was the first astronomer born in South America in 1679, specifically in Santa Fe de la Veracruz, which later became part of the Argentine territory. He never studied in Europe, and with the help of a few Guarani artisans, he built several telescopes with polished crystal quartz lenses and other instruments that allowed him to install an astronomical observatory in the middle of the jungle. His observations led to celestial maps, calendars, and his famous work: "Lunario de un siglo [2]." The first astronomy observatory in Brazil was built around 1640 under the occupation of northeastern Brazil by the Dutch West India Company under the government of Johann Maurits. Maurits hired his own research staff to promote scientific studies in Brazil, among whom was the German astronomer and naturalist Georg Markgraf, who observed the solar eclipse of November 13, 1640. When the Portuguese reconquered the place, this first observatory was destroyed until the emperor Pedro II, an astronomy enthusiast, had a new observatory built in 1845, which operated until 1922 [3].

Therefore, people in Latin America have studied astronomical objects, the light that emerges from them, and the light-matter interaction for thousands of years. Still, it was not until the advent of the laser in 1960 that photonics, the area of science and emerging technologies dealing with the generation and manipulation of light, was born. Photonics, which brought together two already consolidated disciplines, such as optics and electronics, in a new field, covers all technical aspects of the transfer of information with light beams. Also, within a broader vision, it includes manipulating the electromagnetic spectrum from X-rays to microwaves and what is recognized as the next frontier of wireless communications in the terahertz band, between 0.1 and 10 THz.

II. Photonics in Latin America

Immediately after the invention of the laser, Latin American countries began to develop their prototypes, and it was in Argentina where the first ruby and He-Ne lasers were fabricated between 1962 and 1964. Since 1959, there was a group working on quantum electronics led by Federico Westerkamp and a group of brilliant students at the University of Buenos Aires at a time when science flourished in the country [4]. Other scientists specializing in European and North American research centers also returned to the country to work in this emerging field.

Other pioneer scientists introduced laser research and development in the various countries of the region. Rogerio Cesar de Cerqueira Leite put the first ruby laser into operation in Brazil in 1965 in collaboration with renowned Brazilian physicist Sergio Porto, working in the United States in the laser and Raman spectroscopy fields [5]. In 1972, Porto returned to Brazil to join the recently founded UNICAMP, intending to turn the university into an international center for laser development and their applications. Indeed, with the creation of the Gleb Wataghin Institute of Physics in 1974, UNICAMP became one of the centers of the most remarkable expansion and impact in light technologies in Brazil and Latin America. Also, around 1967 in

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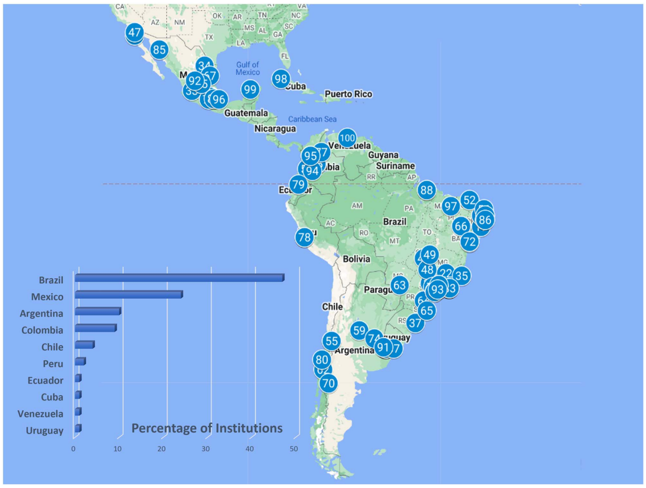

Fig. 1. Map of the 100 most relevant institutions in photonics in Latin America. Source: Scopus, documents by affiliation since 1990, keyword: photonics. In the inset, the percentage of institutions in the top 100 by nation.

Mexico, Daniel Malacara built the first He-Ne laser and, within INAOE (Instituto Nacional de Astrofisica, Optica y Electronica), created the first graduate programs in optics a few years later. In 1980, Malacara founded the CIO (Centro de Investigaciones en Optica) in Leon, entirely dedicated to research in photonics.

The history of photonics in Latin America cannot be divorced from the history of our people who suffered and still suffer from economic and political instability due to various factors that are beyond the focus of this work. As an example of how our experiences as developing countries cross our scientific development, we refer to a talk given by the prominent Argentine physicist Oscar E. Martínez at the Ultrafast Optics XIII conference, held in Bariloche, Argentina, in 2023 [5]. So that, skipping all the events that have happened from the dawn of the laser to the present day, we will only cite some references here that tell part of these stories [6], [7], [8], [9], [10], whereas we will focus on the current landscape in this work.

Fig. 1 shows the hundred most important institutions in which photonics research is carried out in Latin America, evaluated through the number of times they appear as affiliations of the papers or conference communications, using photonics as a keyword. The map shows the non-homogeneous distribution of the institutions, where almost 50% are Brazilian. Fig. 2, top panel, shows the number of publications in the area by country from 1988. As expected, the three countries with a longer tradition in optics and photonics appear in the pole position of publications. Even so, the proximity of two more recent players, Chile and Colombia, is very interesting, both having a prominent role in the scientific work generated. In the case of Chile, an important part of the photonics community is grouped at the MIRO Institute, which is part of the Millennium initiative that began in Chile in 1999 [11] and is currently a program of the National Research and Development Agency (ANID), belonging to the Ministry of Science of Chile. In the long term, the program aims to improve the quality and impact of Chilean research. There are 36 research centers: 15 in natural and exact Sciences and 1 in Photonics. In

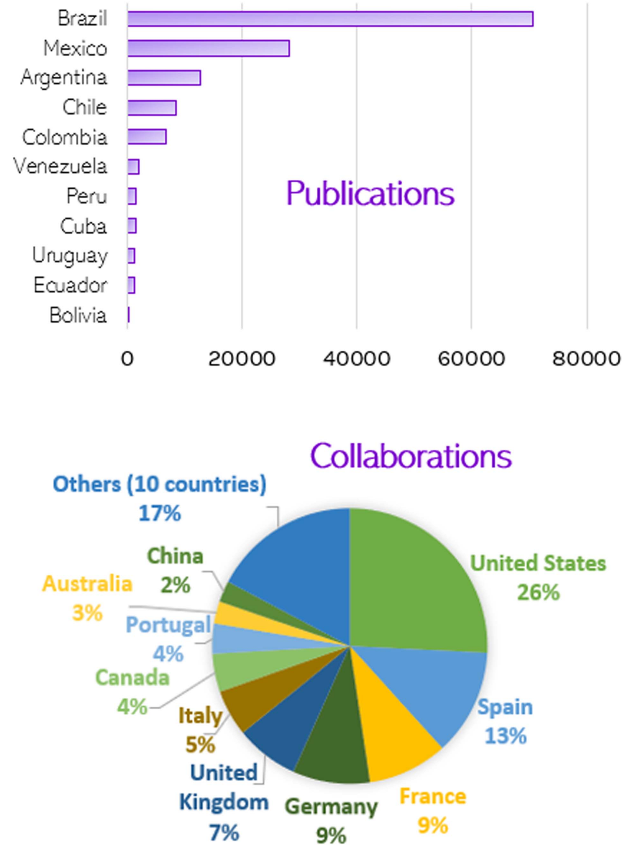

Fig. 2. Top panel: Publications of the leading Latin American players in photonics since 1988. Bottom panel: collaborations between Latin American institutions and countries outside the region, measured by the number of papers published in journals and conferences since 1988. The 20 most frequent partner countries are shown. Keywords: optics, photonics, laser, microscopy, optical communications, optomechanics, and image processing. Source: Scopus.

a different organizational model, leveraged on territorial and regional organizations, the case of Colombia is also interesting; its community began towards the end of the 1980s with a handful of researchers trained abroad and today has around thirty important groups distributed throughout the country, as described in detail in reference [9]. It is worth mentioning here that the Colombian physicist Angela Guzman has been one of the prominent figures who led the development of optics in Colombia and contributed enormously to consolidating a Latin American community in optics and photonics.

Regarding international collaborations, it can be seen in the bottom panel of Fig. 2 that Latin America collaborates mainly with the United States, which makes sense considering the scientific power of that country. But in second place are the collaborations with Spain, which reveal a deep cultural connection, language sharing, and a long history of joint meetings in optics and photonics that began in 1992 with the Ibero-American RIAO meetings. Also, RIAO merged in 1998 with the well-established Latin American OPTILAS conference, whose first edition had been held in Colombia in 1984 [9], [10], [12]. France, Germany, and the United Kingdom are powerful scientific partners as well, followed by countries worldwide. In 1992, the Optical Society of America, today OPTICA, also started a series of Latin America

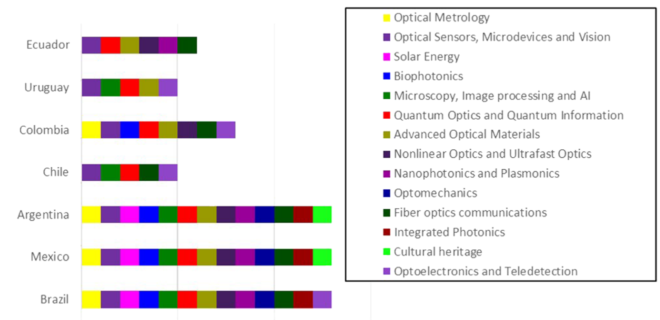

Fig. 3. Basic research topics in photonics for some Latin American countries. The graph was assembled based on the research groups' main works and some published reports. In the acknowledgments section are the names of those referents from the countries that have provided valuable information to assemble the graph.

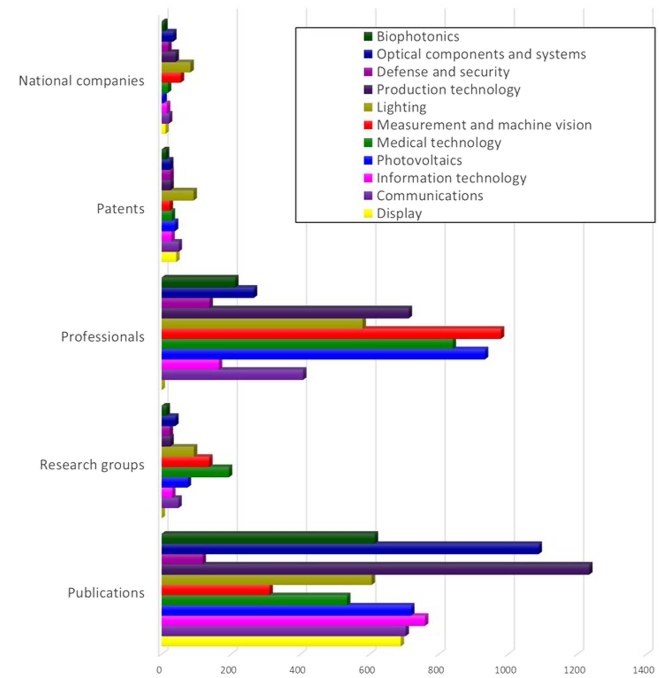

Fig. 4. Data on the innovation ecosystem in Brazil. General comparison between all the innovation segments shown as the different colors. Total number of publications from 2008 to 2018. Total number of research groups from 2008 to 2018. Total number of professionals (researchers and students) from 2014 to 2018. Total number of patents published from 2008 to 2018. Total number of national manufacturers in 2020. All data extracted from [14].

Optics and Photonics Conferences (LAOP), which concentrated over the years Latin American participation in 68% of their presentations, mainly coming from Brazil, Mexico, Perú and Colombia in that order.

Concerning basic research topics, Latin America encompasses a wide variety of subjects developed by research groups distributed throughout the continent. Fig. 3 shows a graph that gives a general idea of the topics, which were grouped similarly to provide a picture of the thematic scope. It is worth mentioning the case of Ecuador, which joined the International Commission for Optics (ICO) in 2015 and which, in the last decade, has tried to expand basic research in photonics and realize efforts to train young students and scientists.

Photonics directly impacts people's lives, and light technologies cross all disciplines, being a field for permanent innovations and the development of new inventions. The United Nations has recognized, by proclaiming 2015 as the International Year of Light and establishing May 16 as the International Day of Light, the importance of raising global recognition of how light-based technologies promote sustainable development and provide solutions to global challenges in energy, advanced manufacturing, communications, health, etc. Globally, the photonics industry continues to exhibit spectacular growth, as shown in SPIE's Optics & Photonics Industry Report 2022 [13]. Business based on photonics technologies anticipates revenues for more than $2.5 trillion, i.e., a share of approximately 3% of the world's economy. Despite the pandemic's impact on supply chains, companies report record profits, showing the strength and demand for photonics-based products and services. Although our countries have reached excellent academic development, they still lack an industry that could drive engineering despite some application success. The only exception is Brazil, which has consistently developed the education, science, technology, and business photonics ecosystem.

In the 2020 report Mapeamento dos principais segmentos do Ecossistema de Fotônica no Brasil [14], from which the data presented in Fig. 4 were extracted, 678 active research groups were identified, growing about 140% between 2008 and 2018. Above 5200 professionals were found working in photonics in educational institutions from 2014 to 2018, where 32.6% are students and 67.4% are researchers. The southeast region (Sao Paulo region), having 36.9% of research groups, presented the most developed scientific ecosystem. The 387 patents published from 2008 to 2018 emphasize the lighting segment, which holds 23.8% of patents. There was a presence of 6528 national companies working with photonics, where 307 are manufacturers of technologies or equipment aimed at developing photonics. Again, the southeast region presented a high concentration of companies. Finally, 385 companies were identified as international companies operating in the domestic market. All these numbers are far from those of any other country in the Latin American region. However, each of the countries in the region is trying with different instruments to connect basic research with the needs of local industry and the population. In Argentina, the National System of Lasers (SINALA), belonging to the Ministry of Science, provides funding to purchase large instruments related to light technologies, focusing on developing science aimed at the different productive sectors. This system has created a roadmap [15] outlining the strategies for achieving these objectives, but the realization is still in its infancy. Among the ProMéxico plans in which the Mexican government proposes roadmaps to implement innovation-focused strategies is Hacia un México más brillante: mapa de ruta de óptica y fotónica, drafted in 2016 [16]. This document highlights the strengths and opportunities to position Mexico as a Latin American leader in the photonics industry, with concrete actions in the three vertices: government, industry, and academia.

III. Plasmonic Nanoantennas As Mechanical Nanoresonators

Nanoantennas or "antennas of light" have revolutionized our understanding of the light-matter interaction at the nano and meso scales. Although humanity has been fascinated by the optical properties of nanoparticles since ancient times, and their beautiful and bright colors were used in stained glass, their physicochemical properties only began to be studied around the 1990s, and the applications exploded about twenty years ago. The name antenna is used because it transforms the propagating electromagnetic energy into concentrated energy, like radio and mobile phone antennas. However, in the case of light antennas, these volumes are nanometric. Then, these small light concentrators can be used in ultrasensitive biochemical sensors, ultra-high resolution microscopy, optical communications, color light conversion, and light enhancers for photovoltaic applications, among many other applications, and in particular, have given rise to paradigm changes such as flat optics or plasmonic photocatalysis [17], [18], [19], [20], [21]. All these ideas are at the frontiers of knowledge today and are at the core of the field of nanophotonics. From 2004 to date, less than 400 papers appeared in Scopus with the keywords "nanoantenna" or "plasmon nanoparticle," originating in Latin American institutions, mainly from Brazil, Mexico, and Argentina. In numbers, the contribution is small- however, with a reasonably good number of 15 citations per work- if compared to the international community contributions to the field, which in the same period is of around 12000 papers.

Within the broad spectrum of phenomena that occur after the optical excitation of plasmonic nanoantennas, we will discuss briefly here their ability to efficiently transform electromagnetic radiation into mechanical energy [22]. Indeed, converted into tiny mechanical resonators after pulsed light excitation, they are able to sense with high precision the mechanical properties of their nanometer environment, as well as to generate hypersonic waves (sound in the GHz and THz range) that travel through substrates in a similar way as seismic waves do on the Earth's surface [23], [24]. In particular, we will briefly review the recent contributions to the field of our group at the University of Buenos Aires and collaborators. For an extensive review of nanomechanics with plasmonic nanoantennas, please refer to our recent publication [22].

Acoustic phonons in the hypersonic range play a critical role in signal processing in wireless communication devices to mediate between microwave radiation and the charge carriers operating various electronic components. Acoustic signals can be filtered, guided, or delayed in a limited space more easily than the original electromagnetic waves [25] because the group velocities of acoustic phonons ($\sim$5000 m/s) are several orders of magnitude smaller than those of photons. Acoustic waves are also important in handling heat dissipation in devices, optomechanics, and evaluation of elastic properties of materials [26], [27]. Thus, full optical generation of acoustic waves from coupling coherent acoustic phonons with the environment is of both basic and technological interest.

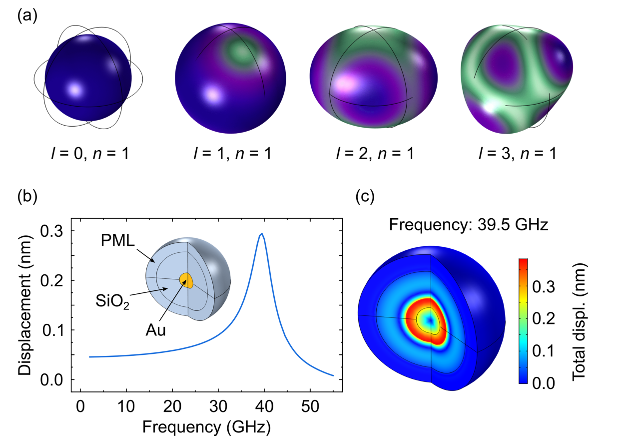

Fig. 5. (a) Simulations of the first normal modes of a gold sphere. The figures correspond to the deformations of the spheres taken at an arbitrary instant of the oscillation. To see the complete simulation performed with the finite element method program COMSOL Multiphysics, go to: http://users.df.uba.ar/hboggiano/StrlMechSims/Gif_1.gif. (b) Simulation of the breathing mode ($l = 0, n = 1$) of a gold sphere of 40 nm radius, surrounded by silica. The vertical axis shows the displacement in nanometers. (c) Snapshot of the dynamical simulation[1] of the main mode in (b).

The most critical parameters of a nanoresonator are the frequencies of its normal modes and their quality factors, which are sensitive to their environment and the way they are excited (optically or mechanically). As an example, Fig. 5(a) shows the frequencies of the first normal modes of a gold sphere and a picture of its deformation at an arbitrary time. These movements result in an efficient modulation of the plasmon resonance, which in a pump-probe experiment can be detected as changes in the transmission of the probe pulse, giving a time-resolved measurement of the coherent phonons generated [22], [28], [29]. Fig. 5(b) shows the simulation of a 40 nm diameter gold sphere surrounded by silica. The oscillation frequency of the free sphere is 38 GHz, while that of the sphere surrounded by silica is 39.5 GHz. Generally, the experimental resolution achieved in a typical coherent phonon measurement experiment is around 0.1GHz, depending on the signal-to-noise ratio.

Finally, we will mention two relevant works of our group in the field of mechanical nanoresonators. In one of them [23], we demonstrated that coherent phonons produced in a source plasmonic nanoantenna couple to the underlying substrate in the form of surface acoustic waves (SAWs), travel through it, and are detected by a receptor nanoantenna in the acoustic far field. The results are summarized in Fig. 6(a), (b). In the other work [30], we propose V-shaped source nanoantennas managing the directionality of the hypersound generated. In the same paper, we also detail how the receptor nanoantenna's frequency response defines the frequency of the mechanical spectrum to be detected. It must be emphasized that all these studies are done on the single particle level and repeated several times on similar systems to obtain the statistics. The central results of this study are presented in Fig. 6(d)–(f).

[1][Online]. Available: http://users.df.uba.ar/hboggiano/StrlMechSims/Gif_2.gif. Author: Hilario Boggiano

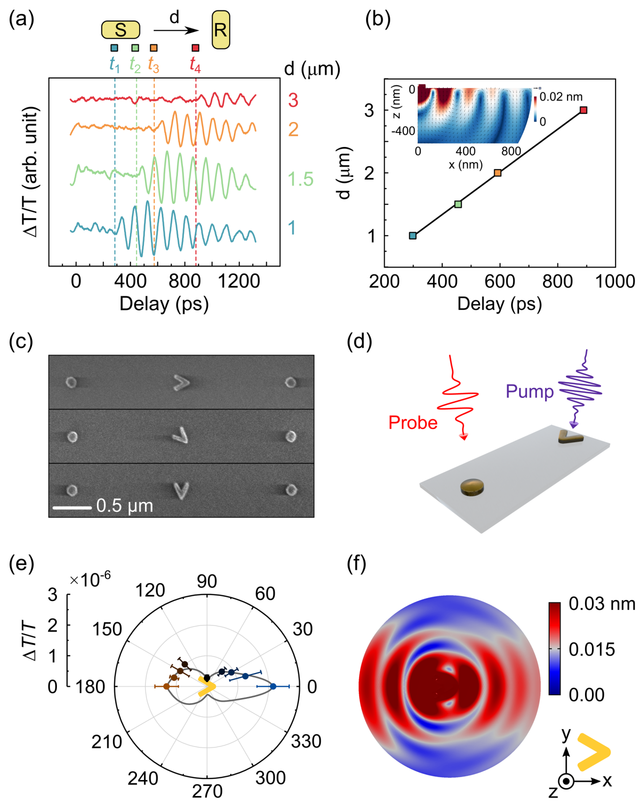

Fig. 6. Hypersound generation and detection with plasmonic nanoantennas. (a) Differential transmission of the probe for the detection of surface acoustic waves generated by a 140 nm long nanorod and detected by another nanorod at varying distances from the source (S). Note that in this experiment, the pump is over S and the probe over the receptor R. (b) Arrival time of the wave (marked with dotted colored lines in (a) at different distances with the corresponding settings that allow calculating the hypersound velocity: (3305 ± 15 m/s). A simulation of SAW propagating through the quartz substrate is included in the inset of the figure. The hypersound penetration is on the order of 200 nm. (c) Electron microscopy images of the systems measured in the experiment with V-shaped gold antennas on a quartz substrate. (d) Schematic of the two-color experiment (pump wavelength: 400 nm; probe wavelength: 800 nm). (e) Polar plot of the experimental SAW amplitudes as a function of detection angle, with the corresponding simulation for the main oscillation mode in (f), which exhibits horizontal directionality like the experimental data. Adapted with permission from references [20], [27].

IV. Conclusion

In this article, we have given a general overview of the situation of photonics in Latin America, starting with a brief historical introduction. We see an important advance in the development of the discipline, especially in the three leading countries, Brazil, Mexico, and Argentina, followed by more recent work done in Chile and Colombia, which is briefly discussed. The case of Ecuador is also highlighted since there has been a growing effort to intensify work on the topic and in training human resources. Other interesting players specializing in fewer topics are Uruguay, Peru, Bolivia, Venezuela, and Cuba. However, there is a pattern in the Latin American region, with the only exception of Brazil, in which advances in basic research are not reflected in products or national companies related to photonics or with an expansion of developments towards products. While countries are making an effort to sustain scientific growth and present roadmaps for the development of photonics in the coming years, there is a great deal of work to be done, which can only be successful if sustained state policies are pursued in promoting science and technology in our countries.

In addition, we have briefly presented the latest results on using plasmonic nanoantennas as mechanical nanoresonators, a subject in the field of nanophotonics developed in our laboratory at the University of Buenos Aires in Argentina. In particular, we have briefly reviewed the most relevant work on the topic, highlighting the potential use of these mechanical nanoresonators to generate, detect, and steer hypersonic acoustic fields in the GHz range of frequencies.

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