A Survey on Microtransformers

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Abstract—The miniaturization of magnetic devices is a subject of enduring interest, since inductors and transformers of very small dimensions are constantly being required for integration into microchips and electrical circuit boards. The main objective of this survey is to supply a compilation of the published research on microtransformers, and to work as a support material, helping in the choice of the most appropriate technology and device configuration for a particular application. The text describes the historical development of microtransformers, the structures in which these devices might be assembled, the various proposed geometries, the fabrication processes, and the type of core used. A brief discussion of equivalent circuit modeling is presented. The current state of the technology in relation to commercial devices is then examined, pointing out some unsolved problems that warrant further studies.

Index Terms—microtransformers, miniaturization, reduced magnetic devices, integrated transformer, power conversion

I. INTRODUCTION

From the early stages of the electronics era, there has been a continuous effort in order to find ways to reduce the size of components. Most electronic components have been compacted considerably, like the transistors, which started with sizes of the order of centimeters and were gradually being reduced, down to the nanometer scale. On the other hand, magnetic components, such as inductors and transformers, with dimensions still in the millimeter range, are considered bottlenecks for the size reduction of electronic circuits. The need for downsizing has mainly been motivated by device integration in electronic circuits and boards.

In this survey, the term “microtransformer” has been applied to small-scale electric transformers that were manufactured using techniques and processes which are not just a mere scaling down of the conventional fabrication methods applied to bulk devices. In some of the published literature, small sized transformers were built just as a proof of concept for testing a specific device configuration or fabrication process. In this survey, we analyzed the scientific articles in which microtransformers were effectively built or used in some application, and we believe that these articles cover almost all devices reported in the literature. The main objective of this work is to present a broad overview of the literature on microtransformers, mainly addressing the issues related to manufacturing processes, types of structure, device geometry, and core materials. A brief analysis regarding the overall performance of microtransformers is also provided. This performance analysis took into consideration the inductance, frequency range of operation and coupling coefficient achieved by the microtransformers reported in the literature. The results show that the frequency range of operation and the inductance values depend on the coil

structures only for values near the lower or the upper limits of those parameters. This work also suggests the need of development of new magnetic materials or new arrangements of the existing ones in order to increase the relative permeability of the cores and increase the inductance values of the windings, and to extend the operating frequency range of the devices.

There is a large number of individual applications for microtransformers, but all of them can be included into one of the following areas: energy conversion, communications, and sensors and instrumentation. This work also aims to provide the necessary information to allow people to choose the appropriate microtransformer, according to the requirements of a specific application. This choice should take into consideration device parameters like frequency of operation, dimensions, inductance and resistance values, turn ratios, quality factors, coupling coefficient, as well as other factors, such as the manufacturing processes and cost. An analysis regarding the current state of development of microtransformers is also provided, pointing out the main problems of the existing devices and suggesting further studies required to solve these issues.

II. HISTORICAL DEVELOPMENT OF MICROTRANSFORMERS

Figure 1 shows the temporal evolution of the academic interest in the development and application of microtransformers between 1990, when the first article using the term “microtransformer” was published, and the year of 2020 [1]. The graph in Fig. 1a shows the number of articles mentioning the term “microtransformer” published in each year, from 1990 to 2020, and the graph on Fig. 1b shows the number of citations to the published works until March 2021. From Fig. 1a, no apparent regularity in the number of publications along the years can be detected, but in Fig. 1b one can observe that the number of citations to the published works shows a clear growth trend until the year 2017, suggesting a persistent demand for small-scale transformer devices, even with the drop presented in the last three years.

Although the graph in Fig. 1a shows only data from 1990, the development of transformers in the millimeter/micrometer scales started in 1969, with the so called “thin-film transformers”, and the first author to report this kind of device was McNichol [2]. In this work, he proposed the use of a gateable thin-film transformer as an alternative to semiconductor circuits for implementation of low level switches. Taking into account that a transformer is essentially a group of coupled inductors, the very early stages of microtransformer development could be traced back to the studies on microinductors, with the first report of a microinductor being a thin-film inductor by

Fig. 1: Publications using the term “microtransformer” between the years of 1990 and 2020: (a) number of publications per year; (b) number of citations of the published works along the years. Source: Web of Science (March 2021).

Fig. 2: Scheme of a three-turn rectangular planar coil.

Yamashita and Mittra in 1967 [3]. No other references mentioning new studies or applications of microinductors or thin-film inductors could be found between 1967 and 1969. In addition, there is a lack of publications (regular papers in scientific journals) reporting research or application of microtransformers and microinductors between 1969 and 1989. The nearest paper about a small-scale transformer has been published in 1988 by Oshiro *et al* [4] describing characteristics of planar transformers. An article reporting a thin-film transformer has been published in 1989 by Wimmers *et al* [5] and another one, reporting an analysis of rectangular spiral transformers, was published in the same year by Boulouard *et al* [6]. Some conference papers were published in the years between 1969 and 1989, most of them reporting development or usage of rectangular spiral transformers [7], [8]. After 1967, the term microinductor was reported again only in 1991 by Matsuki *et al*, [9] and Yamaguchi *et al* [10]. However, back in 1974, the study of a small rectangular planar inductor (see Fig. 2) by Greenhouse, was the first to provide the basis for physical modeling of this kind of device [11].

Although microtransformers have been researched for decades, only a few review papers on the subject have been published until now, but all them are mainly focused on

single subjects [12]–[14]. Thus, this work is aimed to provide a broad overview of microtransformers.

III. KEY TOPICS IN THE MANUFACTURING OF MICROTRANSFORMERS

All articles mentioning the use of microtransformers draw attention to (at least) one of these topics: structure, geometry, core material and fabrication process. Any of these factors can affect everything from design and parameter values (mainly inductances and resistances) to performance (quality factors (Q), coupling coefficient (k) and efficiency). Sub-sections III.A to III.D present figures that provide an overview of the operating frequencies of microtransformers, classified according to the topics previously mentioned (Fig. 3 to Fig. 6). From those figures, one can observe that most of the microtransformers reported in the literature operate at frequencies lower than 10 MHz. Due to the absence of a standard method for characterization of microtransformers, the operating frequencies quoted by different authors may actually represent slightly different quantities. In these figures, the operating frequencies were chosen according to the following criteria: 1) the frequencies explicitly indicated by the authors; 2) the frequencies at the peak value of the coupling coefficient; 3) the frequencies at the peak Q -value for the secondary winding; 4) the resonance frequency for the secondary winding; 5) as a last resort, the frequency at the peak inductance value. Of course, the devices can operate in frequency ranges beyond and/or below those indicated, but the resonance frequency, and to some extent the frequency at which the maximum value of Q occurs, tell us that the device operates well up to such frequencies.

It is worth to mention at this point that the most basic equivalent circuit model for a non-ideal inductor consists of a resistor in series with an inductor, since the conductor that forms the inductor always presents a finite resistance value. Then, the complex impedance Z of a coil is expressed as:

$$Z = R + j\omega L \quad (1)$$

where $\omega = 2\pi f$, with f being the linear frequency of operation, and j is an imaginary number. The real and imaginary parts of the complex impedance provide the resistance and inductance of the coil. That is:

$$\text{Re}(Z) = R ; \text{Im}(Z) = \omega L \quad (2)$$

Thus, the Q -value of a coil in a microtransformer is usually defined as:

$$Q = \text{Im}(Z)/\text{Re}(Z) = \omega L/R \quad (3)$$

Microtransformers that use planar coil structures usually require high Q -values to operate properly.

A. Structures of microtransformers

There are many ways to arrange inductors in order to obtain a magnetic coupling between them, and these arrangements are called structures. All microtransformers found in the literature can be classified into one of these types: *coplanar*, *multilayer* or *solenoid*. Coplanar microtransformers are those in which the coils lie on the same plane, either in interleaved or side-by-side configurations. The multilayer microtransformers have their

Fig. 3: Main operating frequencies of microtransformers according to their structures.

coils on different layers (with or without a magnetic film between them). A microtransformer is said to have a solenoid structure when its coils are wound around a common axis, with a constant winding radius. The distribution of the different types of microtransformer structures according to their operating frequency ranges is shown in Fig. 3.

i. Coplanar

Coplanar microtransformers usually present 1:1 turn ratios, restricting their application to systems that do not require voltage amplification. From Fig. 3 we can see that this structure is used in a wide range of operating frequencies, with an almost uniform distribution among the indicated ranges.

The reduced size, which can be only a few hundreds of micrometers, is the main advantage of the coplanar structure. Another advantage of coplanar devices, especially those without a magnetic core, is that they are usually able to operate with almost constant inductance in a wide range of frequencies (from hundreds of kilohertz to tens of gigahertz). The overall performance of these devices is good, with coupling coefficients higher than 80% and, in some cases, with quality factors ranging from 5 to 15 [15]–[23]. On the other hand, this structure usually leads to inductance values lower than those that can be achieved with other structures. The two highest L -values at the secondary windings of a coplanar microtransformer were 5 μH and 900 nH, as reported by Yamaguchi *et al* [24] and Kahlouche *et al* [25], respectively. In both cases, the microtransformers were composed by spiral-interleaved coils with magnetic films as external cores, but in the first one, the film covered both sides of the coils, while in the second the film was only present between the coils and the glass substrate.

ii. Multilayer

Many of the multilayer microtransformers also have small sizes, but unlike the coplanar devices, they can be built with turn ratios higher than 1:1 [26]–[30]. Like the coplanar devices, multilayer microtransformers can usually operate with almost constant inductance values over a wide range of frequencies. The exceptions are those devices that use magnetic cores/films in their design. Multilayer

microtransformers have been mostly used for operation at frequencies lower than 10 MHz or higher than 1 GHz (see Fig. 3). An advantage of multilayer over coplanar devices is that they can reach higher L -values, up to 500 μH [31]. The performances of multilayer and coplanar microtransformers are comparable, with coupling coefficients higher than 70%, according to the articles that reported this parameter for multilayer devices [24], [26], [28], [32]–[38]. The quality factors of multilayer microtransformers can be higher than 10, as stated by some authors [39]–[41].

It is interesting to notice that the development of microtransformers started with a multilayer device reported by McNichol in 1969 [2]. Unfortunately, that work did not provide values for the main parameters (number of turns, inductance and resistance values, coupling coefficient and operating frequency), which would be useful for comparison with newer devices, giving an indication of the progress in the development of multilayer technology.

iii. Solenoid

Among the different structures, solenoid-type microtransformers can be made with higher turn ratios, with 1:50 being the highest ratio reported [42]–[47]. Regarding the operating frequencies, most of the articles indicate application at frequencies lower than 1 GHz, mainly due to the use of solid cores. The high L -values that can be reached using this structure is another advantage. Macrelli *et al.*, for example, built a ~ 4 mm diameter toroidal microtransformer that achieved 315 μH inductance in the secondary winding [46]. Their prototype had a turn ratio of 1:38 and a coupling factor close to 1 (up to 4 MHz). The windings were obtained by wire bonding over a micromachined ferrite core bonded to the copper layer in a PCB substrate, enabling the coils to be mounted with a small bond pad pitch. In general, the performance of solenoid-type microtransformers is good, with many of them presenting coupling coefficients higher than 90% [48], [44]–[46], [49]–[60] and with some displaying quality factors higher than 10 [46], [47], [55]–[58], [60]–[66].

iv. Comments on the structures

In order to choose the most appropriate structure for a microtransformer, it is necessary to consider the application, the fabrication process and the dimensions available for the device. For example, if an application requires microtransformers with high inductance values, or with a high turn ratio (used for voltage elevation), then the best choice is the solenoid structure. On the other hand, if the application requires a microtransformer with very small footprint and volume, then the coplanar and/or multi-layer structures would be more suitable. These structures can reach very small sizes, with dimensions of only a few micrometers, fully justifying the term “microtransformer”.

B. Microtransformer geometries

Regarding the geometries that can be adopted for a microtransformer, there are many possible arrangements, but the most common ones are bar (or rod/linear), racetrack, spiral and toroidal. Figure 4 shows the main operating

Fig. 4: The bar graph shows the main operating frequencies of microtransformers according to their geometry. The distribution of microtransformer geometries by type of structure is shown in the pie charts. The number of devices is indicated in the slices. *Solenoid shaped **Coplanar and multi-layer.

frequencies of microtransformers according to their geometry.

From Figs. 3 and 4, one can surmise that neither the structure nor the geometry restricts the operating frequency of a microtransformer. However, some tendencies can be noticed: one can observe from Fig. 4 that most of the microtransformers using the racetrack geometry with solenoid structure were designed to operate in the frequency range from 10-999 MHz, while those using racetrack geometry in a coplanar or a multi-layer structure were expected to work at frequencies lower than 10 MHz. One can also notice that the devices using a toroidal geometry were reported to operate mainly at frequencies lower than 10 MHz, while those using spiral geometry operate in all frequency ranges. Coplanar and multilayered devices (which are essentially a pair of planar coils), using spiral, racetrack or other geometries are more commonly used at higher frequencies. The solenoid-type devices, in racetrack and toroidal geometries, tend to be used at low and intermediate frequencies.

Figure 5 shows microtransformers built according to different design principles and typical geometries reported in the literature.

i. Bar/rod/linear

This is a three-dimensional geometry, used exclusively in solenoid-type microtransformers, and can be coreless or have a solid core. This kind of geometry yields good coupling coefficients (higher than 80% in most of the devices analyzed) and can achieve high quality factors (Q -values up to 27 have been reported) [49]–[51], [54]–[57], [60], [65], [67], [68]. On the other hand, microtransformers using this geometry are usually assembled using 1:1 or 1:2 turn ratios, having low inductance values [49], [55], [58], [67], [69]. This can mainly be attributed to the low number of turns in coreless windings. Even when a solid core is used, the inductances are reduced because the cores do not have closed magnetic paths.

In the first work reporting a microtransformer assembled in a bar geometry, Mino *et al.* have prepared a set of six devices with a 4:1 turn ratio [70]. Using a dry process, the devices were built on a 10 μm thick SiO_2 layer with two magnetic coatings. The stacking sequence was: lower magnetic layer – lower coil – center magnetic layer – upper coil, with a total device thickness lower than 300 μm . The authors used a CoZrRe alloy as the core material. As a result, the microtransformer with the highest inductance values ($L_1 = 350$ nH and $L_2 = 40$ nH) exhibited a coupling coefficient of 0.5, which is not a great result in itself, but was the first value reported for this parameter in the development of microtransformers.

ii. Racetrack

The term “racetrack geometry” refers to microtransformers in which the core or the coils are in a shape resembling a racetrack. Any of the possible microtransformer structures (coplanar, multilayer or solenoid) can be made with this geometry [15], [26], [29], [30], [43], [52], [53], [61]–[63], [66], [70]–[84]. In general, the inductance values achieved using this geometry can vary greatly, due to the different parameters involved (structure, dimensions and core used). Racetrack microtransformers assembled in a solenoid structure usually present higher inductance values. Racetrack devices using either a solenoid structure or a coplanar structure with external core usually have dimensions of the order of a few millimeters, while those using the multilayer structure are in the micrometer range.

Regarding the performances, only a few authors determined the k and Q parameters for microtransformers using the racetrack geometry. Some articles reported coupling coefficients for racetrack solenoid devices to be in the 0.5-0.9 range, but in most cases custom-made core materials were used, instead of those commercially available [43], [47], [61], [70], [83]. For the coplanar devices with racetrack geometry, k values up to 0.93 have been reported by Wang *et al.* [71], [78], but inductance values were relatively low (just a few dozens of nH). Ahmed *et al.* were able to build a device with high inductance values ($L_1 = 90$ μH and $L_2 = 164$ μH at 1 kHz) in a footprint area of 2.56×1.24 mm^2 using a solenoid-racetrack with a Ni-Fe Permalloy core [83]. The authors also reported a 73.75% efficiency at 50 kHz using a 1 k Ω load resistor, which is a good result for a microtransformer. Taking into account that the device was built using a MEMS fabrication process, the efficiency can surely be improved by using a material with lower core losses. The assembly can also be adapted, generating a device with a higher turn ratio, instead of the 10:18 ratio adopted by the authors.

iii. Spiral

This geometry is one of the most widely adopted in microtransformers used for application in communications, including at least a pair of planar spiral inductors. These inductors are usually designed according to the classic modeling by Greenhouse [11], [85]–[87]. The spirals can be

Fig. 5: Illustrations of microtransformers according to different design philosophies. These are examples of typical devices reported in the literature.

Fig. 6: Main operating frequencies of microtransformers grouped according to the fabrication processes.

circular, square, elliptical or n -sided polygons, and the coils can be coplanar (interleaved or side by side) or placed in different layers (with or without magnetic layers between the coils) [6], [17]–[19], [22]–[25], [27], [31], [33]–[37], [39]. Due to their compact spiral coil assembly architecture, microtransformers having very small area and volume can be fabricated. The smallest devices ever built had a footprint area $30 \times 30 \mu\text{m}^2$, with inductance values reaching only hundreds of pH [27].

iv. Toroidal

This geometry is exclusively used in solid core solenoid devices and in coreless toroidal microtransformers [42], [44]–[46], [48], [114]–[120]. As a consequence of the solenoid structure, these microtransformers provide the best overall performance parameters, with inductance values up to $400 \mu\text{H}$, quality factors higher than 20 and coupling coefficients higher than 90%. Even if these are actually millimeter scale transformers, they may still be small enough for integration into compact electronic circuits.

Toroidal microtransformers with magnetic cores and 1:38 turn ratios have been reported by Macrelli *et al.* [45]. The authors combined the wire bonding technique and PCB substrates in order to produce low cost 4 mm-diameter devices. They compared the performances of four devices with cores differing in composition and magnetic properties, finding that the core material did not significantly change the k values for a given frequency. On the other hand, the resistance values, which are associated with core losses, were drastically increased by changing the NiZn-based material for a MnZn-based core, leading to lower quality factors. The NiZn-based core material would be a better choice for energy harvesting applications, since it provides lower core losses, allowing more efficient handling of a low energy source.

v. Other geometries

Microtransformers using geometries different from those already discussed have been reported. Some of the examples are: e-shaped, fractal, polygonal and meander [16], [21], [28], [40], [59], [121]–[127]. Most of these singular microtransformers have coplanar or multi-layer structures and present 1:1 turn ratios. The most noticeable exception is a monolithic device with polygonal geometry, developed by Lim *et al.* [28], with a 1:5.8 effective turn ratio. For these unusual geometries, coupling coefficients between 0.45 and 0.92 and quality factors up to 16 have been reported. Maximum inductances were not higher than $3 \mu\text{H}$. It is interesting to notice that a conventional transformer geometry, the EE, was not reported in the context of microtransformers.

C. Fabrication processes

The processes discussed in this work are focused on the fabrication methods applied to the metal windings. Core construction is not addressed, since in many cases the transformers are coreless (or are reported to use air cores).

From all the papers considered in this survey, the main processes reported are CMOS, Microfabrication, Micromachining, PCB and Wire Bonding. Microfabrication and micromachining are the most used processing methods, with $\sim 50\%$ of the reports. Figure 6 shows the main operating frequencies of microtransformers according to the fabrication processes.

It can be seen from the graph in Fig. 6 that the CMOS and PCB processes appear in the extremes of operating frequencies, being the first one mostly aimed to work in the GHz band and the second one most reported to operate below 10 MHz. The micromachining process appears to be homogeneously distributed among the frequency intervals.

The microfabrication-based processes were the most used up to the year 2000, with only a few papers reporting fabrication using micromachining and PCB. Between 2000 and 2010, the fabrication processes have multiplied, including microfabrication, micromachining, PCB and CMOS techniques. Since 2010 the wire bonding technique has been added to the list, although one of the first devices built with this technology appeared in an application bulletin of the Burr-Brown Corporation in 1994 [114]. One of the most versatile processes for building microtransformers with any structure and geometry, is microfabrication [2], [5], [6], [17], [22], [25], [28], [40], [49]–[51], [54], [58], [62], [63], [70], [71], [80], [81], [84], [89], [90], [92], [105], [107]–[109], [122], [128]–[130]. Of course, any of the other fabrication approaches may involve microfabrication in some of the processing steps.

Fig. 7: The bar graph shows the main operating frequencies of microtransformers according to their cores. The distribution of microtransformers by core material and according to structure is shown in the pie charts. The number of devices is indicated in the slices.

An interesting method for building a microtransformer with the multi-layer structure has been developed by Hsu and Chen [37]. Their device, designed for an IC, exhibited a compact layout (92 μm sided), and was built using 90 nm CMOS technology. The configuration with higher turn ratio yielded inductance values of 8.78 nH and 2.43 nH for the primary and secondary windings, respectively. These inductance values could be increased, if a high permeability magnetic material had been used as a core. However, magnetic materials are not a normal component in the process used to build this microtransformer. In order to include a magnetic core, it would be necessary to develop a process for fabricating a six-layer metal device, while including another compatible process for the core. This is not a trivial task due to the risk of contamination between steps and the possible need for additional planarization steps.

D. Solid core and coreless devices

There are microtransformers that use a solid (bulk) core or a magnetic film, and there are those that are “coreless” (also called “air core” transformers). About 42% of the devices described in the papers considered in this work are coreless transformers. The main operating frequencies of microtransformers according to their cores are shown in Fig. 7. One can see in the graph that most of the cored devices operate in the low and intermediate frequency ranges, while most of the coreless devices were reported to operate in the GHz band. The decision to have a core (or not) is also related to the intended application area of the microtransformer (discussed in section V).

The use of cores made from magnetic materials (in bulk or thin film form) has been always derived from the need for improving device performance. The main benefits are an increase in the inductance values and an improvement of the coupling coefficient through a better concatenation of the magnetic fluxes in the windings. Among the

microtransformers incorporating magnetic cores, the majority of the core materials are Fe-based, being FeNi and Ferrites the most commonly adopted (see Fig. 7).

Since the relative magnetic permeability (μ_r) of the core material depends on the operating frequency, the inductance values for microtransformers with solid cores are constant only within a small range of frequencies, while the coreless devices are able to keep a constant inductance value across a wide range of frequencies.

In the solid core microtransformers, the resonant frequency is always very far from the frequency range where the inductance values are constant (or have the maximum value). However, in the air core devices, the frequency of resonance is closer to the f value where L_{max} occurs and not far from the frequency range where L has a constant value. Yamaguchi *et al.* [24] performed an interesting work, comparing devices built with or without a magnetic core. For this purpose, they fabricated microtransformers using different materials in the core (CoFeSiB and CoNbZr), with different stoichiometries for each material. In that work, the authors have shown that the magnetic cores not only increased the inductance values of the individual windings, but also improved the coupling coefficient. On the other hand, it became clear that the core losses were much smaller for the coreless devices, which also exhibited higher cut-off operating frequencies.

Regarding the use of solid cores, most magnetic materials are subjected to the Snoek’s limit, which defines the frequency range in which the real part of the magnetic permeability (μ') of a material remains constant, exhibiting a phenomenon in which the higher the μ' value at low frequencies, which is associated with higher inductance values, the lowest is the frequency where it begins to decrease [131], [132]. This phenomenon is accompanied by an increase in the value of the imaginary part of the magnetic permeability (μ''), that is related to the magnetic losses, which is smooth in the frequency range where μ' is constant, but sharp when approaching to a threshold frequency. The joint behavior of μ' and μ'' is what determines the useful operating frequency range of a material as a core of a transformer.

Since the Snoek’s limit of a material changes according to its chemical composition, more research is required in order to obtain compounds that are able to increase the μ' value while extending the Snoek’s limit [131]. In this way, the development of microtransformers would be greatly favored, being possible to significantly reduce their sizes, but maintaining high inductance values.

IV. MODELING AND COMPARISON WITH COMMERCIAL DEVICES

A. Equivalent circuit modeling

Many of the published works show comparisons between simulations and measurements of some key parameters of microtransformers, but only a few authors explicitly reported the equivalent circuit model used in their simulations. The most basic model for a microtransformer found in the literature is a circuit joining two inductors with

a capacitor parallel to both. There are also more complex models which include a large number of additional components, accounting for the interactions among the components of the microtransformer itself and with the substrate on which it is assembled. This kind of model are most useful for CMOS and/or RF compatible transformers, where the semiconductor substrate itself as well as the devices built onto it can induce several parasitic effects.

In general, the results of parameters like k , L and Q provided by equivalent circuit models are in good agreement with the measured values. Comparisons among models can be useful, especially for the characterization of devices, and should be taken into account in the design phase of microtransformer development.

B. Comparison with commercial devices

Since we restricted the term “microtransformers” to small-scale electric transformers manufactured using techniques other than the ones applied to conventional transformers, we now adopt the term “commercial device” for the small-scale transformers commercially available.

Commercial devices are currently built with high turn ratios (up to 1:150), and they can present high inductance values as well as coupling coefficients higher than 95%. Further, these parameters are almost constant over a wide frequency range, due to the use of solid magnetic cores with an air gap. However, the commercial devices, due to their fabrication technologies, developed for macroscopic dimensions, cannot have their sizes reduced below the millimeter scale.

Another advantage of microtransformers (besides their size) is that most of them can be built-in or embedded in an integrated circuit (usually CMOS) or a PCB. When the microtransformers are assembled in solenoid-shape with toroidal or racetrack geometries, the coils of primary and secondary windings are separated from each other, avoiding inter-winding stray capacitance, which is a common effect found in commercial devices due to winding superposition.

Regarding the commercial devices assembled in millimeter-scale sizes, we can take as examples two devices using 1:10 turn ratios: The first one has a footprint of 4 mm × 4 mm, with inductances $L_1 = 2.0 \mu\text{H}$ and $L_2 = 20 \mu\text{H}$ [133], and the second is smaller, having a footprint of 3.2 mm × 2.5 mm with inductances $L_1 = 7.0 \mu\text{H}$ and $L_2 = 70 \mu\text{H}$ [134]. The inductance values were measured at 100 kHz in both cases and no information has been provided on their performance at different frequencies. Non-commercial devices assembled in the same scale present maximum inductance values considerably higher than the commercial ones (up to 400 μH for L_2 in [46], for example). On the other hand, a slightly bigger commercial device (4.5 mm × 4.8 mm footprint), assembled with a higher turn ratio (1:150 ratio) exhibits $L_2 = 1800 \mu\text{H}$, which is more than four times bigger than the value obtained with the microtransformer previously mentioned [135].

In order to replace the commercial devices, the microtransformers need to achieve higher turn ratios and provide high L - and k -values, with both not changing significantly with the frequency. Faster, simpler and

cheaper fabrication processes would also be highly desirable. The high L -values, in both primary and secondary windings, are needed to minimize possible perturbations derived from external magnetic fields. The coreless microtransformers present L - and k -values that are almost constant for a wide frequency range but have low L -values. On the other hand, microtransformers with solid cores can reach L -values that are only one order of magnitude lower than those for commercial devices are, but the dependency of μ_r with the operating frequency makes the L parameters to change accordingly.

Of course, the use of a microtransformer or a commercial device will also depend on the application for which it is required (the subject of the next section).

V. MAIN APPLICATIONS OF MICROTRANSFORMERS

Microtransformers are widely employed in a large number of applications that can be broadly classified in the major areas of energy conversion, communications and sensors/instrumentation. The objective of this section is to clarify the most important features of the devices reported in each of the mentioned areas, providing more detailed information when appropriate.

A. Energy conversion

This area has been mentioned in almost 40% of the papers analyzed in this work [15], [22], [24], [31], [39], [40], [42]–[47], [50], [52], [54], [58], [59], [62], [66], [67], [70]–[73], [79]–[81], [84]–[91], [93]–[99], [101], [105], [116], [120]–[122], [131]–[134]. Some of the examples of specific applications in this area are DC-DC converters, energy harvesting, and power systems on chip.

In the energy conversion area, about 46% of the devices were designed to operate in frequencies lower than 10 MHz, while 40% operated in the frequency range from 10 to 100 MHz. Most of the microtransformers projected to work in energy conversion were assembled according to the solenoid structure, and many of them incorporated a solid core. This was something to be expected, since in these applications, the equipment usually works at low frequencies, but requires high inductance values, coupling coefficients close to unity and quality factors as high as possible, in order to minimize losses and optimize the energy conversion efficiency. Of course, another point that stimulates the use of solenoid structures in microtransformers designed for energy conversion is the possibility of easily building devices with high turn ratios.

Midorikawa *et al.* demonstrated that the performance of microtransformers could be improved, even with a spiral assembly, by employing a ferrite film between the coils [31]. The improvement in efficiency was larger in the frequency range from 3 to 100 kHz, increasing from 0-50% to 65-85%. Energy conversion demands high-efficiency devices in order to reduce power losses.

B. Communications

Publications reporting the development of microtransformers for communications are about 34% of

the works analyzed [6], [16]–[19], [21], [23], [28], [32], [34]–[39], [48], [49], [51], [52], [55], [60], [61], [63], [68], [74], [75], [82], [83], [95], [103], [107], [110], [121]–[123], [136]. This includes applications like UHF and VHF circuits and microwave monolithic integrated circuits.

Regarding the main frequencies used in the communications area, almost 17% of the reported devices were designed to work below 10 MHz and the same percentage aimed to work in the range between 10 to 999 MHz. As expected, about 64% of the devices working in communications operate at frequencies higher than 1 GHz, in the radio-frequency band used by cell phones since the beginning of this century. Accordingly, most papers describing microtransformers working in this frequency range have been published from the year 2000 onwards.

Unlike the energy conversion area, the microtransformer structures for communications are quite well distributed among coplanar (~36%), multilayer (~33%) and solenoid (~31%). Two thirds of the devices are coreless, which is a required condition for having stable inductance values in a wide range of frequencies. This guarantees high quality factors at higher frequencies, since Q is proportional to f but, on the other hand, leads to low inductance values, as mentioned in section III.D. Good coupling coefficients have been reported, in many cases higher than 90%, and the turn ratios are close to one for almost all devices. The electronic devices developed for communications do not require microtransformers with high turn ratios, mainly because they are not used to rise voltage signals, but for signal isolation and conversion.

C. Sensors and instrumentation

This area of application has been less reported than the others, with only about 10% of the total number of articles [56], [78], [105], [109], [111], [112], [114], [116], [117], [124], [129], [137]. Sensing devices and signal isolation are examples of specific applications in this area.

Due to the small number of publications focusing on microtransformers for sensors and instrumentation, the only noticeable point is that all the devices were designed to work at frequencies lower than 200 MHz. Not all publications mention inductance values, but the highest one reported was 30 μH , in a solenoid microtransformer with toroidal geometry. The solenoid structure has been adopted in about half of the microtransformers designed for this application area. Regarding the other building parameters (geometry, fabrication process and core used), no clear trend could be discerned.

VI. CHALLENGES FOR MICROTRANSFORMER DEVELOPMENT

The development of microtransformers remains an open research field. Most of the standing questions are related to design and performance, but there are also open issues regarding scalability and the effect of the substrates on which the devices are built. Furthermore, the miniaturization itself is a major concern for some applications, especially those requiring high inductance and high aspect ratio. In addition, the development of core

materials with high relative permeability, stable in a wide frequency range, is required to keep the inductance values constant.

A. Design

In general, researchers start the design of a microtransformer by establishing a desired size for the component, which is usually related to the lowest dimension allowed by the manufacturing process. The desired voltage amplification or turn ratio is taken into consideration, depending on the application, and all the other parameters are derived from these. There are also situations in which the initial parameters are only the primary and secondary inductance values. In these cases, the resulting device will deliver only what is allowed by the design parameters and fabrication process, and not necessarily, what is required by the final application. Of course, some of the electrical parameters of a microtransformer, like the inductance and the resistance, can be estimated by using the information on geometry, conductivity of winding material, core permeability, etc. However, it must be emphasized that such parameters cannot be chosen after the size and manufacturing process have been determined. Therefore, it is still a challenge to develop microtransformers with the exact values of electrical parameters required by an application. This is the most noticeable difference between the design processes of microtransformers and conventional transformers. The conventional devices are designed starting from the desired voltage amplification, operating frequency and output power, and, after that, all the other parameters (size, number of turns, structure, core material, etc.) are stipulated and/or calculated from these three first.

B. Performance

It is a big effort to achieve the optimum performance in a microtransformer: efficiency and coupling coefficient as close as possible to 100% and 1.0, respectively, with quality factors greater than 10 for a wide frequency range. All of these parameters are linked to the design of the device. The efficiency, in particular, will depend strongly on the load and input power, which are parameters that depend on the application. Then, in this case, the starting points are the parameters required by the application, but keeping in mind that these parameters will be limited by the desired and/or required size of the device.

C. Substrate effects

For high frequency (HF) and microwave (MW) applications, the substrate in which the microtransformers are to be built must be carefully chosen due to the possibility of undesired propagation of electromagnetic waves, resulting in interference on other elements of the circuit. Silicon and silicon oxide are widely used substrates for HF devices, but ceramic materials are considered more appropriate for HF and MW due to their low losses in this frequency range, and also because most ceramics are temperature-stable [138]–[143]. However, until now, there

are no reports of microtransformers built on ceramic substrates for HF and MW applications. Glassy materials also present low losses in HF and MW frequencies, but they are more susceptible to temperature variations.

Ng *et al.* [144] studied the substrate effect in RF microtransformers built on Si. For this study they developed a transfer procedure, indicated the maximum available gain (G_{max}) as a figure-of-merit for this kind of transformer, and compared G_{max} and other parameters, before and after the substrate transfer procedure. All parameters were improved after changing the substrate from Si to quartz, and this result is likely related to the lower conductivity of quartz.

There is another issue related to the substrate: the parasitic effects. They concern especially the microtransformers built using planar coils, but any device using thin films will be also affected. Once again, ceramic or glassy materials could reduce parasitic effects; however, the deposition of metallic films on these materials is still less developed than on Si substrates.

D. Scalability

Another challenge in microtransformer development is scalability, meaning the possibility of adapting device size to specific demands without compromising the main parameters, and keeping the performance of previously tested devices. A good example of this can be seen in the work published by Tiemeijer *et al.* [145]. The authors described the development and characterization of a scalable on-chip transformer based on techniques developed to create scalable equivalent-circuit models for on-chip transformers and inductors [146]–[148]. The gain obtained for different transformer winding arrangements was almost the same, but the measured impedances were very different.

Scalability should be one of the most difficult barriers to overcome, since the main parameters of a microtransformer are the inductances of its windings, which are directly linked to device geometry.

VII. CONCLUSIONS

One of the points highlighted in this survey is the lack of a standard characterization method for microtransformers. Considering that the coupling coefficient is one of the main characteristics of a transformer, one would expect this parameter to be reported in most articles, but unfortunately, this is not the case. Inductance, resistance, and quality factor are reported for only one winding in most cases. Microtransformer efficiency is also an important feature; however, it was neglected in most works. Based on this information, one could say that the adoption of a standard method to characterize microtransformers would be useful for both research and commercial purposes.

There is a discrepancy between the frequencies where L -values are stable and those where the peak values of k and Q occur. This indicates that the design of circuits that use microtransformers must take into account these limitations. It also suggests that further studies to develop

microinductors and microtransformers might evolve into a convergence of these two frequencies.

Regarding microtransformer geometry, structure and core, the choices must be made according to the intended application, which will also define the size of the device and its fabrication process. One should always take into consideration that the values of electrical parameters and the performance would also be a consequence of those choices.

One of the main problems in microtransformer development is the difficulty of planning a device with exact values of electrical parameters and with good performance. These problems are related to the fact that the size is the first thing being considered when a microtransformer is designed. Scalability is a minor problem and more difficult to be solved. Future research can be performed in order to find design methods that avoid the mentioned problems and consolidate the microtransformers as dependable components to be used in electronic circuits.

Substrate effects must be taken into account only in devices that operate at higher frequencies, especially those using planar coils, since they are subject to both frequency losses and parasitic effects.

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