Report on benchmarking and TRL assessment of chiral magnonic logic gates and magnonic field programmable gate arrays

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Abstract

The primary idea underpinning project "Magnonic Artificial Neural Networks and Gate Arrays" (MANNGA) is that the resonant concentration of incident spin wave energy in magnonic resonators should enhance both their nonlinear response and the performance of devices based on this nonlinearity. Work package 3 of the MANNGA project is devoted to development of resonator-based chiral magnonic logic gates (CMLGs) and magnonic field-programmable gate arrays (mFPGAs) in comparison with their equivalents without the resonator structures. Here, we evaluate MANNGA's CMLG and mFPGA technologies against their achieved technology readiness levels (TRLs) as well as benchmarks available from literature. We concluded that the CMLG technology remains at TRL2, which is however on par with the benchmarks available elsewhere. Solid TRL3 and possibly TRL4 is achieved for MANNGA's mFPGA based on networks of all-YIG conduits, while TRL3 may also be achieved for MANNGA's mFPGAs based on 2D CMRs and CMR-NUMs on timescales of two-three years.

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I. Introduction

The primary idea underpinning project "Magnonic Artificial Neural Networks and Gate Arrays" (MANNGA) is that the resonant concentration of incident spin wave energy in magnonic resonators should enhance both their nonlinear response and the performance of devices based on this nonlinearity. The resonators represent soft magnetic overlayer structures strategically located above a magnonic medium. Due to the magneto-dipole interaction between the structure and the medium, the structure's local modes can couple to and resonantly scatter spin waves travelling in the medium [1,2], with both the coupling and scattering often having a distinct chiral character. The resonantly enhanced nonlinearity is expected to benefit spin wave computing, which is an essentially nonlinear process. In particular, the power consumption of resonance-assisted devices is expected to be reduced.

Work package 3 of the MANNGA project is devoted to development of resonator-based chiral magnonic logic gates (CMLGs) and magnonic field-programmable gate arrays (mFPGAs) in comparison with their equivalents without the resonator structures. Here, we evaluate the devices against their counterparts demonstrated elsewhere ('benchmarking') and assess the associated technology readiness levels (TRLs) achieved in MANNGA. Two types of resonator structures are discussed here, leading to two distinctly different resonant scattering effects. The structures of the first type, called here chiral magnonic resonators (CMRs), follow the ideas from [3,4], whereby the spin waves propagating in the medium and the local modes of the overlayer structure have the same frequency. The structures of the second type exploit Fabry-Pérot resonances [2,5] formed due to SW reflection from magnonic dispersion mismatches at interfaces between yttrium-iron garnet (YIG) regions with and without a metallic magnetic overlayer; the structures are called here magnonic Fabry-Pérot resonators (mFPRs). In mFPRs, the incident SW energy is resonantly concentrated in the YIG region under the overlayer (rather than in the overlayer itself as in CMRs), allowing the structures to benefit from the low damping achievable in the YIG medium.

The report is organised as follows. In Section II, we describe the methodology of the assessment. In the subsequent sections, we summarise the evaluation results for CMLGs (Section III) and mFPGAs (Section IV). Section V contains our conclusions.

II. Methodology

II.A. Technology Readiness Level evaluation

The evaluation of TRLs is done using the following classification from [6]:

- TRL1 Basic principles observed
- TRL2 Technology concept formulated
- TRL3 Experimental proof of concept
- TRL4 Technology validated in lab
- TRL5 Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL6 Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL7 System prototype demonstration in operational environment
- TRL8 System complete and qualified
- TRL9 Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies, or in space)

For each of the technologies covered by this report, we have aimed for TRL3 - experimental proof of concept.

II.B. Benchmarking

For the purpose of benchmarking, we have used our existing knowledge of the relevant scientific and technological landscape, supported by searching the scientific literature and attending the relevant scientific conferences but avoiding "blaming and shaming" sources of artificially boosted claims. Where possible, we identify and quantify key performance indicators (KPIs) of the devices and then compare KPIs of devices in MANNGA and those demonstrated elsewhere.

III. Chiral magnonic logic gates (CMLGs)

III.A. TRL evaluation for CMLGs

In the course of MANNGA, both CMRs and mFPRs have been shown to have a strongly nonlinear response in SW transmission [4,5], paving the way to designing MANNGA's CMLGs, as discussed in deliverables D3.1 and D3.2. Experimentally, MANNGA's leading designs of magnonic resonators and CMLGs exploit mFPRs with composition and geometry similar to those reported in [5]. We have established that the incident SW energy is resonantly concentrated in the

YIG region under the overlayer, and the energy concentration leads to the mFPRs' enhanced nonlinear response to the excitation. The response is still, however, described well by our model developed for the case of energy concentration in the overlayer itself [4].

The key requirement imposed on the CMLGs in their evaluation is that their logic inputs and output must be defined using the same ranges. This is to ensure that the logic gates can be concatenated into more complex architectures, as done in the case of the semiconductor-based logic. The ranges are however not exact but are allowed to vary in order to maximise the fraction of the input parameter space in which the gate delivers the targeted performance. This fraction represents the primary KPI of a particular logic gate, while its value for a universal logic gate (e.g. NAND) could then be considered as a KPI for the technology.

As described in deliverable D3.2, the best KPI values achieved in MANNGA are 0.915 for NAND and 0.872 for AND gates that use mFPRs. The KPIs are both below 1, which does not allow us to claim achievement of TRL3 for the technology.

III.B. Benchmarking of MANNGA's CMLGs

Magnonics has long been fuelled by hopes for using spin waves in energy-efficient data processing. Although the focus of the related research (including that in MANNGA) has now largely shifted towards neuromorphic computing and machine learning, the early hopes were associated primarily with creation of magnonic logic gates, with several designs put forward, including some implemented experimentally. Nonetheless, many of the proposed devices are not magnonic logic gates per se, while most of the others are linear, with the nonlinearity (and so, their ability to perform the computation) resulting from the way how the measurement results are interpreted. Moreover, the unwanted crosstalk between the amplitude and phase of the gates' output signal has never been addressed properly, until perhaps the latest report on the topic [7]. The latter shows how two magnonic AND gates (based on YIG waveguides) are cascaded but does not present evaluation of the gates' performance for any suitable ranges of the logic inputs. This does not allow us to evaluate performance of their gates in terms of the KPI introduced above. We note however that the power levels used in [7] are of the order of 10 dBm, which is two orders of magnitude greater than in the CMLGs described in deliverable D3.2.

IV. Magnonic field-programmable gate arrays (mFPGAs)

IV.A. TRL evaluation for mFPGAs

In the context of MANNGA, mFPGAs are broadly understood as multiple input / multiple output (MIMO) magnonic devices [8] whose functions could be programmed using their internal degrees of freedom. The latter include but are not limited to global and / or local magnetic field (which may be static or time-varying), SW frequency, micromagnetic magnetic configuration / texture. Three different approaches to mFPGA construction have been considered. Two of these are based on 2D CMRs with nanoscale dimensions. Our modelling of mFPGAs consisting of 2D CMRs with a quasi-uniform magnetisation are described in deliverable D3.3, while deliverable D3.5 is devoted to 2D CMRs with nonuniform magnetisation (CMR-NUMs). Neither of the approaches have resulted in experimental demonstrations of mFPGAs within MANNGA lifetime. Therefore, neither of these two approaches has reached TRL3, albeit this can still change not too long after the MANNGA project's end.

Our leading approach is based on building mFPGAs using networks of all-YIG magnonic conduits, as described in deliverable D3.4. These mFPGAs achieve circa 95% accuracy in digital classification tasks, even under noise levels approaching 100%. Reliable performance is achieved over a wide frequency range of 0.5 – 3.0 GHz as the applied bias magnetic field is varied from 2 to 40 mT. The area efficiency expressed in tera-operations per second per square millimetre (TOPS/mm^2) is 1.85 TOPS/mm^2 for a 12 × 12 μm^2 Y-shaped convolutional processing unit. These results constitute a successful experimental demonstration of the technology in the lab and justify our achievement of TRL3 for this mFPGA type. Moreover, the mFPGAs device have been used as convolutional neural networks (CNNs) validated in three benchmark tasks: handwritten digit recognition (MNIST, 96.2% accuracy), MRI image classification (81.5%), and classification of Parkinsonian gait signals (90.8%). Depending on the degree in which these tests reflect "real-world conditions", our results may constitute a successful experimental validation of the technology in the lab and may justify our achievement of TRL4 for this mFPGA type.

IV.B. Benchmarking of MANNGA's mFPGAs

All of the mFPGAs in MANNGA are based on spin wave scattering and diffraction, either resonance-enhanced, as in deliverables D3.2 and D3.5, or non-resonant, as in deliverable D3.4 and previous publications [9,10,11]. However, only the mFPGA from [11] is both implemented experimentally and used to perform computation. The latter demonstrations are however limited to elementary logic operations, majority gate, and a half-adder. None of the logic gates operate with consistent logic ranges and would not therefore pass the conditions imposed on MANNGA's CMLGs (Section III.A). The advantage of the mFPGAs from [11] is that they do not require an additional in silico output layer, as all of MANNGA's approaches assume. This is achieved through using around 50 of 100 mA scale current loops to control the spin wave scattering and diffraction inside the mFPGA. The associated energy cost is likely to be higher than that required to implement the in silico output layer in MANNGA's mFPGAs. Ultimately, the two approaches could only be discriminated between in a back-to-back comparison when implemented in the same operational environments. The comparison might be undertaken in future, as the technologies are evaluated against TRL5-7.

VII. Conclusions and outlook

In this report, we have evaluated MANNGA's CMLG and mFPGA technologies against their achieved TRLs as well as benchmarks available from literature. The CMLG technology remains at TRL2, which is however on par with the available benchmarks. Solid TRL3 and possibly TRL4 is achieved for MANNGA's mFPGA based on networks of all-YIG conduits, while TRL3 may also be achieved for MANNGA's mFPGAs based on 2D CMRs and CMR-NUMs on timescales of two-three years. The nearest available benchmark is given by the mFPGA built using an array of current loops, although it does not allow for a direct comparison with MANNGA's approaches.

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