Report on benchmarking and TRL assessment of LPE YIG, magnonic reservoir computing, and magnonic recurrent neural networks

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Abstract

We evaluate MANNGA's magnonic reservoir computer (mRC) and magnonic recurrent neural network (mRNN) devices in terms of their achieved and prospective technology readiness levels (TRLs) and benchmark results achieved for equivalent technologies elsewhere. TRL3 is likely justified for mRC, while it is only TRL2 for the mRNNs. MANNGA's mRC and mRNN compare well to their counterparts demonstrated elsewhere. Furthermore, MANNGA has fully achieved its goal to develop reliable and scalable production of 3-inch wafers with LPE YIG films of sub-µm thickness, achieving TRL4 in this research direction.

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I. Introduction

The main idea of and now the major fundamental discovery in project "Magnonic Artificial Neural Networks and Gate Arrays" (MANNGA) is the resonant concentration of incident spin wave energy in magnonic resonators. The associated increase of the spin wave amplitude enhances the resonators' nonlinear response. This nonlinearity may be expected, in turn, to benefit performance of a resonator-based magnonic reservoir computer (mRC) and magnonic recurrent neural networks (mRNNs), which are targeted in work package 4 of the MANNGA project. Both mRC and mRNNs deal with time-domain data encoding / multiplexing and feature recurrent interneural connections, yielding the long fading memory property needed for computing. The connections are implemented, however, differently in MANNGA's mRC and mRNNs. As described in deliverable D4.1, MANNGA's mRC contains a single magnonic resonator, while its recurrent connections are implemented using an electrical active feedback line, creating an active ring topology [1]. As described in deliverable D4.2, MANNGA's mRNNs contain two or more resonators with the recurrent connections implemented via spin waves bouncing back and forth between them. So, mRNNs may be passive devices. However, they may also have an active feedback line added to them and may have their properties varied in time, thereby implementing time-domain training.

The resonators used in the mRCs and mRNNs are of the Fabry-Pérot type. They exploit Fabry-Pérot resonances [2,3] formed due to SW reflection from magnonic dispersion mismatches at interfaces between 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 chiral magnonic resonators [4,5]. So, minimisation of spin wave losses in YIG becomes even more important than usual, leading us to opt for using YIG films grown by liquid phase epitaxy (LPE) as the magnonic medium.

In this report, we assess the technology readiness levels (TRLs) achieved in MANNGA in development of mRCs and mRNNs and evaluate the devices against their counterparts demonstrated elsewhere ('benchmarking'). In addition, we benchmark and evaluate TRL achieved in MANNGA for fabrication of 3-inch wafers of 50 nm thin LPE YIG films.

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 mRCs (Section III), mRNNs (Section IV), and LPE YIG growth (Section V). Section VI contains our conclusions.

II. Methodology

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 the mRC and mRNN technologies, we have aimed for TRL3 - experimental proof of concept, while MANNGA's description of action foresaw a possibility of achieving TRL4 for the LPE YIG growth.

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. 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. Magnonic reservoir computers (mRCs)

III.A. TRL evaluation for mRCs

As described in deliverable D4.1, we have designed and experimentally implemented an mRC employing an mFPR fabricated on an LPE YIG delay line. The performance of the mRC has been tested using standard binary and floating data benchmarks. The best performance so far has been achieved for 500 μm long magnonic delay lines based on 177 nm thick (001) YIG films with a 30 nm thick, 1000 nm wide CoFeB-based mFPR. The best binary benchmark scores are 99.5% for parity(3) and 73.8% for parity(4) tests, and the score of 100% is consistently obtained for parity(2) test. The best floating-point benchmark score is 90.1% for NARMA10(5) test. The results lead us to conclude that the mRC concept pursued in the MANNGA project has been proven experimentally, i.e. TRL3 is justified by the results. As a disclaimer, we note however that the scores vary as a function of the SW carrier frequency. The fast variation correlates with the feedback ring modes and is expected to persist even when the mFPR is absent. There is also a slower variation as the carrier frequency approaches that of the Fabry-Pérot resonance (1.5 GHz). The nature of these variations is still under investigations, and so, we cannot, at this stage, claim achievement of TRL4 for the mRC technology. Moreover, validation of the latter against a wider range of benchmark tasks [7] (ideally, with a more straightforward relevance to practical applications) will be required for the technology to progress to higher TRLs.

III.B. Benchmarking of MANNGA's mRCs

MANNGA's binary benchmark score of 100% for parity(2) exceeds the result reported for plain YIG mRC in [1], where parity(3) and parity(4) tests have not been performed. The best floating-point benchmark score of 90.1% for NARMA10(5) test also represents the first benchmark reported for this class of spin wave based mRC devices. Looking across the wider range of RC architectures but limiting ourselves to those in spintronics [7], we note that there is still a significant disparity in terms of the scores and methodologies of their evaluation. However, given that results for test where the performance is poor are not usually published, we note that only few studies present test results for NARMA10 and none goes beyond this benchmark test (Supplementary Table 1 in [7]). On a qualitative level, our results therefore compare well to those reported in the leading studies elsewhere.

IV. Magnonic recurrent neural networks (mRNNs)

IV.A. TRL evaluation for mRNNs

The development of the mRNN technology in MANNGA has not progressed beyond numerical simulations. So, the technology has only reached TRL2. This is however an achievement, since the concept pursued has emerged in the course of the MANNGA project and had not existed prior to its beginning. Based on the solid results obtained numerically, it is conceivable that TRL3 will be achieved on timescales of a few years, depending on personnel funding available to complete the experimental evaluations.

IV.B. Benchmarking of MANNGA's mRNNs

The mRC benchmark tasks are also suitable for evaluation of the performance of MANNGA's mRNNs, with some scores available for numerically computed results. Defining the root normalized mean squared error (RNMSE) and the normalized root mean square error (NRMSE), also known as normalized root mean squared deviation (NRMSD), as described in [8], we obtain a RNMSE value of 0.262 and NRMSE value of 0.0476 for our best numerical implementation of NARMA10 using a two-mFPR-based mRNN. Our NRMSE value of 0.0476 is better 9i.e. smaller) that the NRMSE value of 0.2 achieved in [9], the only entry in [7] offering a comparable result.

V. 3-inch wafers of 50 nm thin LPE YIG films

V.A. TRL evaluation for growth of 3-inch wafers of 50 nm thin LPE YIG films

As part of the MANNGA project, INNOVENT has strengthened its leading position in the LPE YIG technology by scaling up it to 3-inch wafers with 50 nm thin YIG films. The goal was to develop a stable/repeatable large-scale deposition process for 3” YIG wafers. During development, INNOVENT evaluated the reproducibility of the deposition process and achieved high homogeneity of the most important key film parameters across their diameter and from wafer to wafer. Sub-100 nm thin 3-inch wafers were successfully grown, see for example Figure 1. As foreseen in the proposal, this constitutes achievement of TRL4 for the growth of ultrathin LPE YIG films.

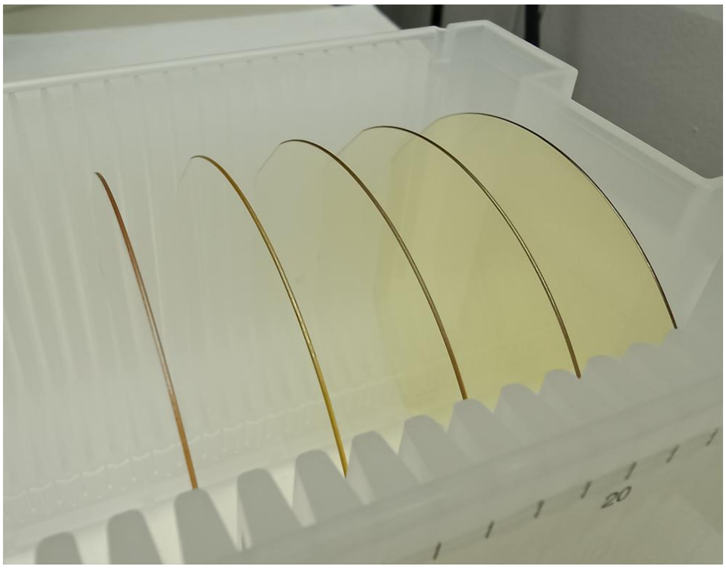


Fig. 1 From left to right: 3-inch wafers of YIG films with thicknesses of t = ~20nm, ~30nm, ~50nm, ~70nm, ~90nm.

V.B. Benchmarking of the developed technology of fabrication of 3-inch wafers of 50 nm thin YIG films

The YIG film perfection developed as part of the MANNGA project is comparable to or better than that specified in the literature for comparable thin films with dimensions of 1 inch or less. Table 1 and the references contained therein confirm this statement.

Table 1. Key parameters of (111) YIG films on GGG substrates.

Thickness (nm)	$\Delta H_{p\text{-}p,0}$ (Oe)	$\Delta H_{p\text{-}p}$ @15 GHz (Oe)	$\alpha_{\|\|}$ ($\times 10^{-4}$)	Deposition method	Reference
103	0.4	1.2	1	3" LPE	MANNGA
75	1.9	2.2	0.5	Sputtering	[10]
56	1.3	1.6*	0.6	PLD	[11]
55	0.3	1.4	2	3" LPE	MANNGA
22	6.4	6.9	1	Sputtering	[12]
23	1.2	2.4	2	PLD	[13]
20	1.4	2.6	2	PLD	[14]
22	0.6	1.8	2	3" LPE	MANNGA

* 12 GHz

V.C. Market analysis

During the MANNGA funding period, we are not aware of any reports of competitive activities to develop sub-100 nm thin YIG films on 3-inch wafers. Therefore, to the best of our knowledge, INNOVENT is the only research institute that can supply YIG films with a diameter of 3-inches and a thickness in the nanometer range.

When searching for competitors, a study names the following companies as globally competitive suppliers of garnets, particular for magneto-optical garnets, (https://www.datainsightsmarket.com/reports/yig-magneto-optical-material-1152414). However, most of them manufacture single crystalline bulk material and ceramic material. To our best knowledge, only GRANOPT and Matesy are capable of growing YIG films on substrate wafers up to 4 inches in size.

- **GRANOPT CO., LTD., Japan (**www.granopt.jp/en/product.html**)**

Manufacture and sale of garnet film Faraday rotators

- **Crystal Systems Corporation, Japan,** https://www.crystalsys.co.jp/en/company

  Manufacture and sale of bulk Faraday rotators (5.5 mm diameter)

- **Coherent Corp., USA,** https://www.coherent.com/company

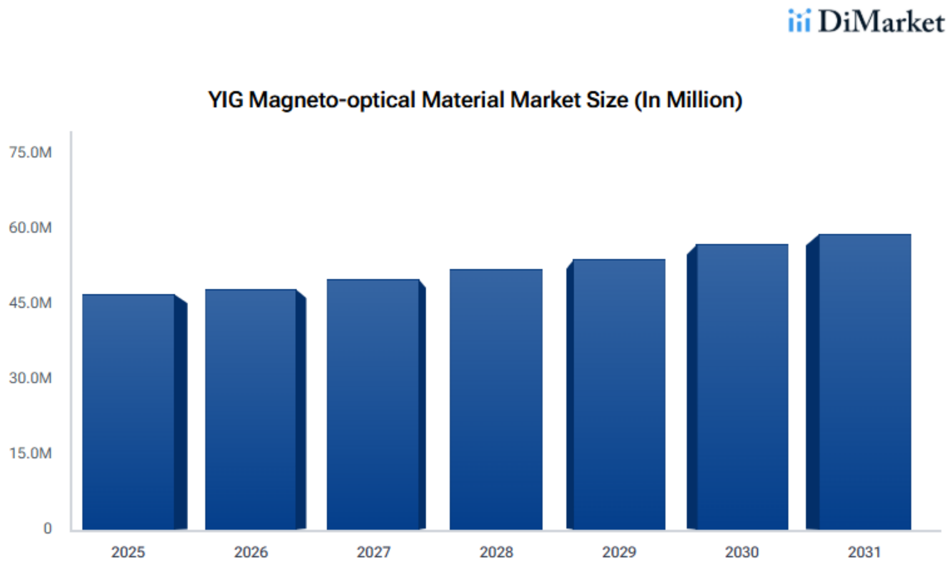
  Manufacture of ceramic YAG ($Y_3Al_5O_{12}$) for solid-state lasers/ optical components

- **OXIDE Corporation, Japan,** https://www.opt-oxide.com/en/
- Manufacture and sale of bulk Faraday rotators (5.5 mm diameter)
- **Matesy GmbH, Germany:** https://matesy.de/en/

  Global leader in high-quality single-crystal yttrium iron garnet (YIG) films

- **Deltronic Crystal Industry Inc./Isowave, USA:** info@DeltronicCrystals.com or info@isowave.com

  Manufacture and sale of bulk Faraday rotators for magneto-optic applications



"The major players in the YIG magneto-optical material market—Granopt, II-VI, OXIDE, Matesy, Deltronic Crystal Industries, and Hefei Kejing—are actively engaged in research and development to enhance the performance and reduce the cost of YIG materials." (https://www.datainsightsmarket.com/reports/yig-magneto-optical-material-1152414)

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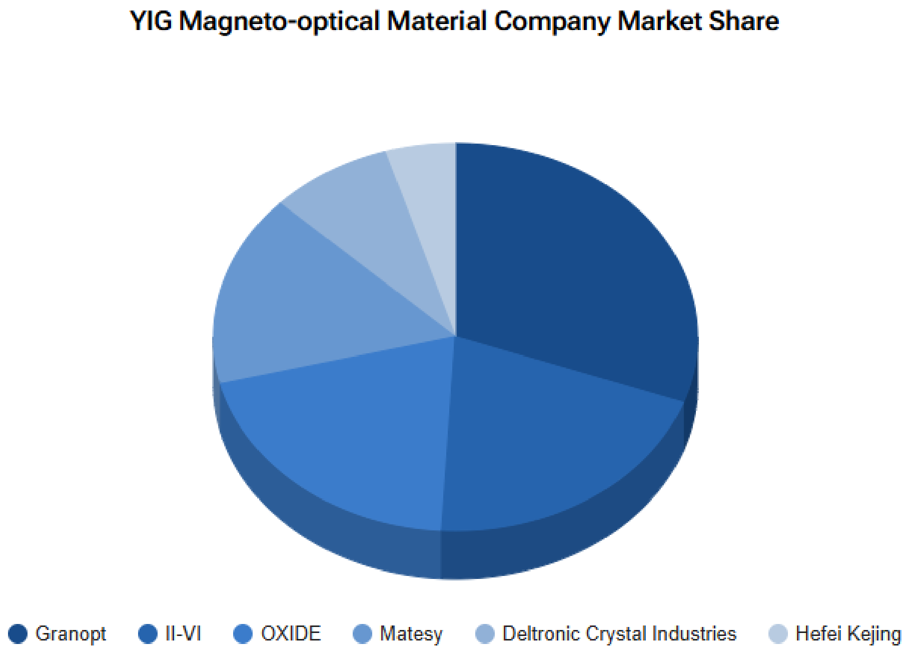

"The optical isolator segment is expected to dominate the market due to its extensive use in high-speed optical communication systems and increasing demand for data transmission applications. This segment's growth is propelled by the ever-increasing need for high-bandwidth, low-loss optical communication networks for data centers, telecommunications infrastructure, and consumer electronics" (https://www.datainsightsmarket.com/reports/yig-magneto-optical-material-1152414).

VI. Conclusions and outlook

In summary, we have evaluated MANNGA's mRC and mRNN devices in terms of their achieved and prospective TRLs and results achieved for equivalent technologies elsewhere. TRL3 is likely justified for mRC, with some quibbles related to our incomplete understanding of the origins of the performance shown. Yet, it is only TRL2 for the mRNNs, which has not progressed to an experimental demonstration within the lifetime of MANNGA. However, MANNGA's mRC and mRNN compare well to their counterparts demonstrated elsewhere.

INNOVENT has achieved one of MANNGA's goals to develop reliable and scalable production of 3-inch wafers with LPE YIG films of sub-µm thickness, which are characterized by high perfection of their surface, microstructure, and excellent magnetic damping properties. INNOVENT is now in a position to transfer its ultrathin LPE YIG growth technology at the 3-inch level to interested companies, such as the spin-off company Matesy GmbH (Germany) or other competing companies based in Europe. These results therefore represent a strategic advantage not only for MANNGA's technology, but also for other technologies based on branches of spintronics in which YIG is actively used.

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